TEKNILLINEN KORKEAKOULU
Sähkö- ja tietoliikennetekniikan osasto

Timo Lindfors

Dropsonde for high altitude platform application

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Työn valvoja Professori Martti Hallikainen

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Tässä diplomityössä tutkitaan korkealta laukaisualustalta pudotettavan mittalaitteen suunnittelun lähtökohtia. Nämä pudotettavat mittalaitteet - dropsondit - mittaavat ilmakehästä vertikaalin profiilin. Nykyisin käytössä olevat dropsondit pudotetaan miehitetyistä lentokoneista, joissa dropsondin valmius ja kunto tarkastetaan ennen pudotusta. Tulevaisuuden ilmakehäntutkimussuunnitelmissa dropsondien osuutta pidetään tärkeänä. Tulevaisuuden suunnitelmat vievätkin dropsondeja korkealla lentäviin heliumnosteisiin ilma-aluksiin, joista dropsondeja pudotetaan automaattisesti. Tämä asettaa uusille suunniteltaville dropsondeille aivan erilaiset toimintavaatimukset.

Diplomityö käsittelee yleisesti nykyistä Vaisala Oy:n valmistamaa dropsondia sekä analysoi erilaisia laukaisualustoja. Työssä keskitytään tutkimaan yhden laukaisualustan - ICARUSS alustan - asettamia vaatimuksia uudelle dropsondille. Näistä vaatimuksista tärkeimmäksi nousee dropsondin kylmänsietokyky. Kaikkia vaatimuksia tutkitaan ensin teoreettisesti ja teorian pohjalta laaditaan testit dropsondin eri osakokonaisuuksille. Testit kuvataan yksityiskohtaisesti ja niiden tulokset analysoidaan. Työn lopussa on yhteenveto dropsondin eri osakokonaisuuksien toimivuudesta tässä ICARUSS-alustan asettamassa ympäristössä sekä ehdotuksia jatkokehityksestä.

Avainsanat: Dropsondi, ilmakehänmittaus, korkealla lentävä laukaisualusta, kylmänsieto

Helsinki University of Technology | Abstract of Master's thesis

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This Master's thesis examines the design requirements for a high altitude platform dropsonde. Dropsondes measure a vertical profile of the atmosphere. At present dropsondes are deployed into the atmosphere from a manned aircraft, where the condition of the dropsonde can be verified prior to the launch. Future atmosphere research programs envision the use of dropsondes as very important. The future research programs plan to take dropsondes to high altitude platforms, where the dropsondes will be deployed automatically. This sets whole new requirements for high altitude platform dropsondes.

This thesis analyses the present dropsonde manufactured by Vaisala Oy on a general basis and examines different envisioned platforms. One high altitude platform - the ICARUSS platform - is studied in detail. The design requirements for the new dropsonde issued by the ICARUSS platform will also be studied. One of the most important requirements is the low temperature tolerance of the ICARUSS dropsonde. All of the requirements are first analyzed theoretically, and from this a full set of tests for the ICARUSS dropsonde is derived. These tests are described in detail and the test results analyzed. The thesis concludes what solutions have to be implemented on the ICARUSS dropsonde and what the future design requirements are.

Keywords: Dropsonde, atmospheric research, high altitude platform, low temperature tolerance

Alkulause

Tämän diplomityön suunnittelu aloitettiin alkuvuodesta 2001. Tarkoituksena Vaisalalla on selvittää mitä erilaisia tekijöitä uuden sukupolven dropsondin suunnittelussa täytyy ottaa huomioon ja miten nämä tekijät vaikuttavat dropsondin kehitystyöhön. Työni sain suorittaa Vaisalan dropsondi-linjalla, jonka johtajalle Ilkka Ikoselle kuuluu suuri kiitos työn mahdollistamisesta. Ohjaajani Kimmo Ristolainen ansaitsee erityisen kiitoksen työn tarkasta ja mutkattomasta ohjaamisesta. Myös Teknilllisen Korkeakoulun avaruustekniikan professorille Martti Hallikaiselle kuuluu kiitokset työn tarkastamisesta, ohjaamisesta sekä opetuksesta opintojeni aikana. Avaruustekniikan laboratorion osaavasta opetuksesta haluan erityisesti kiittää Kimmo Rautiaista sekä Simo Tauriaista .

Työn aikana jouduin toistuvasti käyttämään dropsondilinjan resursseja kysellessäni dropsondien sielunelämästä ja tästä suuri kiitos koko Vaisalan dropsondijoukoille:

Tapani Antila, Marko Keskinen, Johanna Lentonen, Pasi Mäkinen,
Matti Patteri, Ville Puhakka, Ossi Vasko sekä Anu Äijälä.

Kiitokset myöskin vanhemmilleni, jotka auttoivat opintojeni etenemistä huomattavasti.

Ja ehdottomasti kiitokset myös Tanjalle - kaikesta.

Vantaalla 301101PE

Timo Lindfors

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TABLE OF ABBREVIATIONS

HAP	High Altitude Platform
ICARUSS	Inter Continental Atmospheric Radiosonde Upper-air Sounding System
UAV	Unmanned Air Vehicle
GMT	Greenwich Mean Time
NCAR	National Center for Atmospheric Research (USA)
RD93	Present Vaisala dropsonde
GPS	Global Positioning System
AVAPS	Airborne Vertical Atmospheric Profiling System
PTU	Pressure, temperature and humidity
THORPEX	The Hemispheric Observing System Research and Predictability Experiment
FASTEX	Fronts and Atlantic Storm-Track Experiment
NORPEX	North Pacific Experiment
WSR	Winter Storm Reconnaissance
LEO	Low Earth Orbiting
GAINS	Global Air-Ocean In-Situ System
NASA	National Aeronautic and Space Administration (USA)
ERAST	Environmental Research Aircraft and Sensor Technology
WMO	World Meteorological Organization
c_p	Specific heat capacity
$I_{s/a/p}$	Intensity of Solar/Albedo/Planetary radiation
$A_{s/a/p}$	Area exposed to Solar/Albedo/Planetary radiation
a	Albedo coefficient
F	View factor
α	Absorptance coefficient
ε	Emittance coefficient
σ	Stefan-Boltzmann constant
e_d	Dielectric variable
C_D	Drag coefficient
S	Projected surface area
κ	Conduction coefficient
h	Convection coefficient

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1. INTRODUCTION

This Master's thesis examines the need for a new dropsonde system, tests different solutions and suggests concrete measures to be taken in its design. The thesis also examines the conditions this new dropsonde system has to withstand, and analyses the relevant aspects involved. This introductory chapter describes the contents of the thesis on general basis.

1.1 Background for the study

The need for a new - next generation - dropsonde arises from the growing global need to perform more accurate and reliable meteorological observations over areas at present void of weather instruments. At present, atmospherical observations are mainly conducted with soundings of different kinds. A radiosonde sounding is the most used method for this purpose and it is used to gather synoptic - regular - in-situ data of the atmosphere. Radiosonde sounding is conducted with helium filled balloons to which a measuring device - a radiosonde - is attached. The balloon lifts the radiosonde to altitudes of 30 km and allows the radiosonde to measure a vertical profile of the atmosphere. The measured factors include temperature, pressure, humidity and wind direction and speed. These soundings take place at fixed locations around the world and these locations, located mostly on land, form the network needed to form a scientific meteorological model of the current atmosphere.

The reason to collect meteorological data more efficiently derives from the fact that many of the atmospheric phenomena, such as storms and local climatic changes are formed in areas where no observations are made. Oceans are the main example of these areas. Several international projects have been launched to come up with an answer to gather data from these data-sparse areas and thus improve meteorological predictions. These projects rely heavily on the use of special radiosondes - dropsondes. [1] [2]

The present dropsonde application produced and manufactured by Vaisala does not meet the requirements needed for this new use of dropsondes. The present dropsonde is deployed from manned aircraft where the initial set-up for the dropsonde is conducted before the launch, which is impossible for HAPs - high altitude platforms. These high altitude platforms are the envisioned carriers from which the next generation dropsondes will be deployed into the atmosphere. The operational altitude of HAPs is designed to reach altitudes above 20 km and the dropsondes should be deployed automatically after long periods in these upper air conditions. The HAPs are designed to operate in these data sparse areas and thus improve the meteorological sounding-grid. Key features in the design of the next generation dropsonde include power consumption, weight of the dropsonde and cold resistance of the dropsonde components.

1.2 Scope of the study

This Master's thesis includes a detailed description of present day dropsondes - what they are, how they are used and where. The present day Vaisala dropsonde will be addressed in detail. Detailed descriptive analysis of the different modules or building blocks of the dropsonde will follow next. In this chapter the reader will be introduced in detail to all the modules that make up the dropsonde. This analysis will be followed by an analysis of different platforms used to launch a dropsonde. The main focus is on the high altitude platforms and particularly on the ICARUSS platform that is addressed in a separate chapter. The next generation dropsonde will be designed for this ICARUSS platform and its development will be studied next. This study includes the requirements the new dropsonde has to meet to operate reliably and accurately in this extreme environment. The differences between the existing dropsonde and the new will also be scrutinized to gain understanding of the concrete need for this next generation dropsonde. This ends the theoretical analysis and research of the thesis and is followed by the experimental part and tests.

The first tests and design feasibility studies will be conducted on separate modules, such as batteries and transmission circuits. This thesis focuses entirely on individual module testing and suggests the best alternatives for the future prototype to be built. Each of the modules is tested individually in simulated environments to examine its behavior and to learn which solution is appropriate for the prototype.

This theoretical study and testing phase will be analyzed in the conclusion of the thesis. The methods used to analyze the theoretical factors and the tests will be addressed and the modules' performance to satisfy the need for high altitude platform applications is analyzed in detail.

Sources are indicated with an uppercase number in brackets - i.e. [1]. The list of sources is included at the end of the thesis.

Appendices are specified with a bold capital A and a specified number in brackets - i.e. **[A1]**. The list of Appendices is included at the end of the Thesis.

1.3 Structure of the study

Chapter	Description	Goals
1. Introduction	Outlines the scope and the focus of this Master's thesis and describes the work in general terms.	The idea, scope and the structure of the thesis are understood.
2. Dropsonde	Briefly addresses the history of dropsondes, the present day Vaisala dropsonde and the general use of this dropsonde.	The concept of dropsonde becomes familiar. The use and benefits of dropsondes are understood.
3. Modules of Dropsonde	Different modules that make up the dropsonde will be studied in this chapter.	Understanding of the modules and their individual needs.
4. High Altitude Platform	The term HAP is described and addressed. The focus of the chapter includes most of the different HAP applications envisioned.	The term high altitude platform - HAP - is clear. The difference between platforms is understood as well as the purpose of their use.
5. ICARUSS Platform	ICARUSS HAP application is analyzed in detail in this chapter.	ICARUSS platform and the conditions of the operation environment are understood.
6. Next Generation Dropsonde	This chapter addresses the requirements and design parameters of the next generation dropsonde.	The requirements issued by ICARUSS HAP to the dropsonde are understood.
7. Module Tests	Module tests include all the tests conducted to analyze the individual behavior of the dropsonde modules and their results.	What is tested and how. Results of the module tests.
8. Conclusion	Throughout analysis of the thesis.	Understand the concept of prototype designs.

2. DROPSONDE

This chapter describes the general concept of dropsondes and their purpose and use in atmospheric research. The present day Vaisala dropsonde along with its development history is included to gain further insight to the dropsonde design stages. Also included is the history of dropsondes and the main future trends and plans for dropsonde applications.

2.1 General Description

Dropsonde has been developed from its balloon-carried counterpart - a radiosonde. To understand the nature of these measurement devices, a short summary on the use of radiosondes is included here. This is followed by a general description of dropsondes.

2.1.1 Synoptic Measurement by Radiosondes

Radiosondes are the main application used to collect data from the atmosphere. A radiosonde is a measuring device, which is released into the atmosphere with the help of a helium or hydrogen filled balloon as illustrated in *Figure 1*.

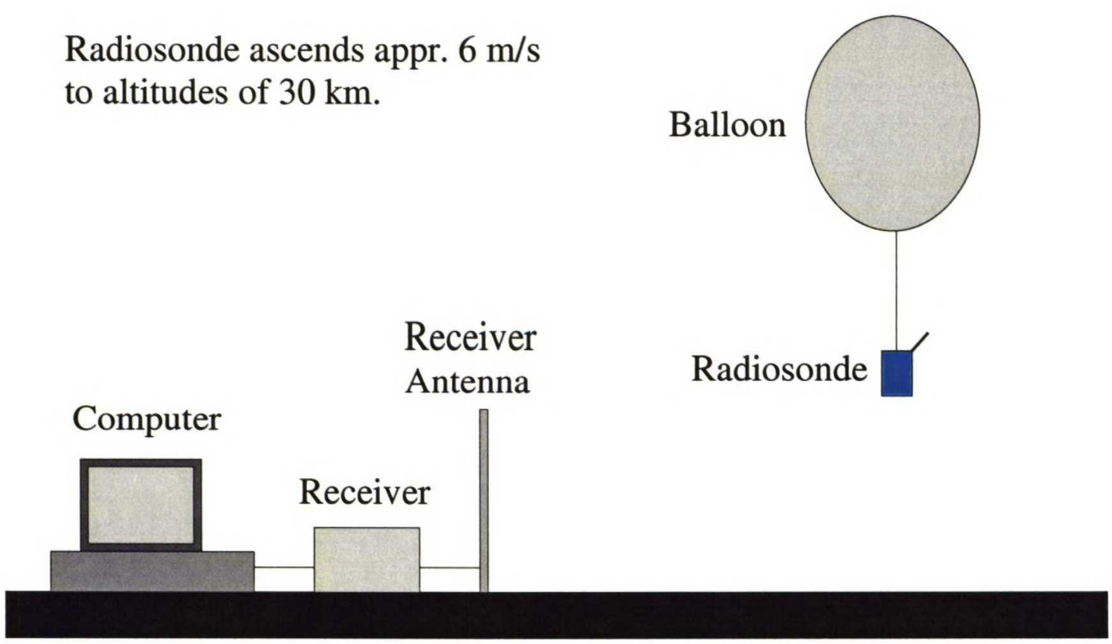


Figure 1. Radiosonde Operation.

A radiosonde measures the temperature, humidity, pressure and wind speed and direction as it ascends in the atmosphere at constant intervals - each data point once per second. This measurement data is transmitted back to ground, where ground equipment consisting of a receiver antenna, receiver and a computer, collect the data and process it further. Radiosondes are being released throughout the world from fixed ground stations at given time instants. These instants are agreed to be 00:00, 06:00, 12:00 and 18:00 GMT. Collected data is then brought together from all the stations, processed and sent worldwide to the end users. This network of measurement stations and their operation constitutes to the main and most important means to collect synoptic data from the atmosphere.

2.1.2 General Description of Dropsondes

A dropsonde, on the other hand, works opposite to its balloon-carried counterpart. As the name suggests, this type of radiosonde is taken to a desired altitude and then dropped. A dropsonde then starts to measure the atmosphere same way as an ascending radiosonde with the exception of descending while measuring. Dropsondes generally use parachutes to slow the rate of descent to a desired level and, like radiosondes, dropsondes are designed to be single-use devices.

This method of placing the dropsonde to a specific altitude and location is a major factor in the dropsonde systems. This is generally referred as the platform for a dropsonde and these platforms come in many different forms.

Figure 2 illustrates dropsonde application with some of the platforms presented. Presently manned aircrafts are used to launch a dropsonde from altitudes of approximately 5 to 10 km. Also model scale rockets are used to take special payload dropsondes to altitudes of 1 km and deployed there. Future designs include constant level balloons that cruise in the upper atmosphere in altitudes of 20 km and house a number of dropsondes, which are dropped at steady intervals. Airplanes and UAVs - Unmanned Air Vehicles - are also planned to be used as dropsonde platforms. All of these platforms could take a dropsonde to various altitudes and locations. This variety of platforms also requires specific attention to the design of the dropsondes to suit all of these existing and planned platforms.

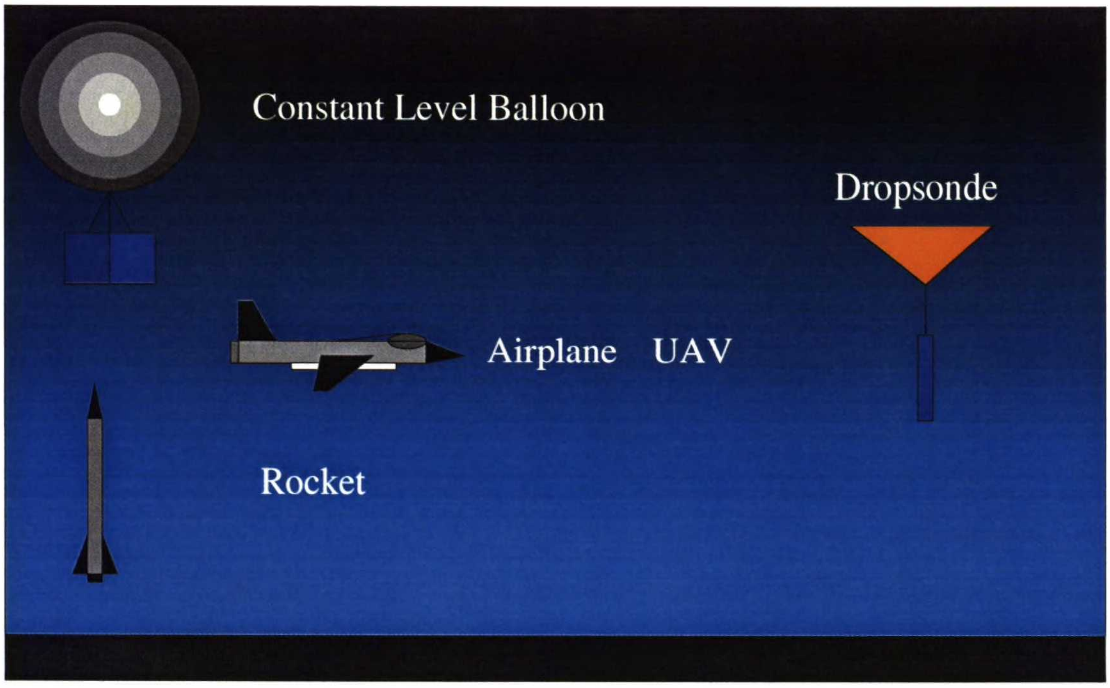


Figure 2. Dropsonde Platforms.

2.2 History of Dropsondes

First dropsondes were designed in the early seventies by USA's National Center for Atmospheric Research - NCAR - for Global Atmospheric Research Program and the intent was to use these dropsondes to study the influence of tropical oceans on weather conditions. This was done with dropsondes due to the fact that other measuring devices were difficult to use over oceans, where no firm sounding station could be set up. After the initial use and experience, dropsondes were plunged into hurricanes forming in the oceans to get first hand data from this violent atmospheric phenomenon. As a result the knowledge of hurricanes and other weather patterns forming in the oceans increased and the dropsonde application gained a strong acceptance among researchers. Since then the development of dropsondes continued, driven by NCAR and Vaisala. However, in 1994 both sides agreed to focus on developing a single dropsonde instead of two independent projects. This cooperation unified the dropsondes and lead to the present day situation of Vaisala constructing dropsondes under NCAR license. [3]

2.3 RD93 - Dropsonde

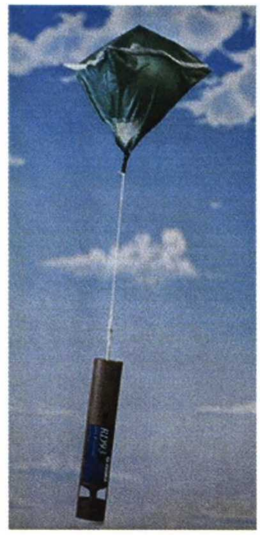


Figure 3. RD93 Dropsonde.

The present day dropsonde manufactured by Vaisala is the sonde illustrated in *Figure 3*. This RD93 dropsonde represents the only existing dropsonde in the markets today. This version has been used since 1994 and the use has been limited to platforms, where initial check-ups and dropsonde condition verifications are possible. Basically this means a manned aircraft, which is the only present platform for RD93. The RD93 dropsonde itself consists of tubular outer shell, as seen in *Figure 3* and an elastic spring to which a square-cone parachute is attached. The dropsonde's interior consists of electronics circuit, GPS and transmission antennas, batteries and separate sensor unit as illustrated in *Figure 4* next page.

The parachute is deployed after a streamer whirls around the bodywork of the dropsonde and pulls the parachute, to which it is attached, free from the parachute compartment. This is necessary to avoid too early parachute deployment after release from high velocity aircraft. The streamer delays the deployment and allows the dropsonde to slow down before the actual parachute deployment. GPS - Global Positioning System - antenna points upward from the dropsonde and the satellite data is processed by a GPS receiver. The GPS receiver takes advantages of the Doppler shifts of individual satellites transmissions to come up with the wind solution and hence no GPS code is used in the RD93 GPS package. Lithium batteries provide the power for the dropsonde by feeding 18 Volts to the circuitry. The transducer unit processes the sensor output and feeds this crucial sensor information to a microprocessor which in turn sends the data to 400 MHz transmitter which consequently sends the information back to the onboard receiving system in the aircraft.

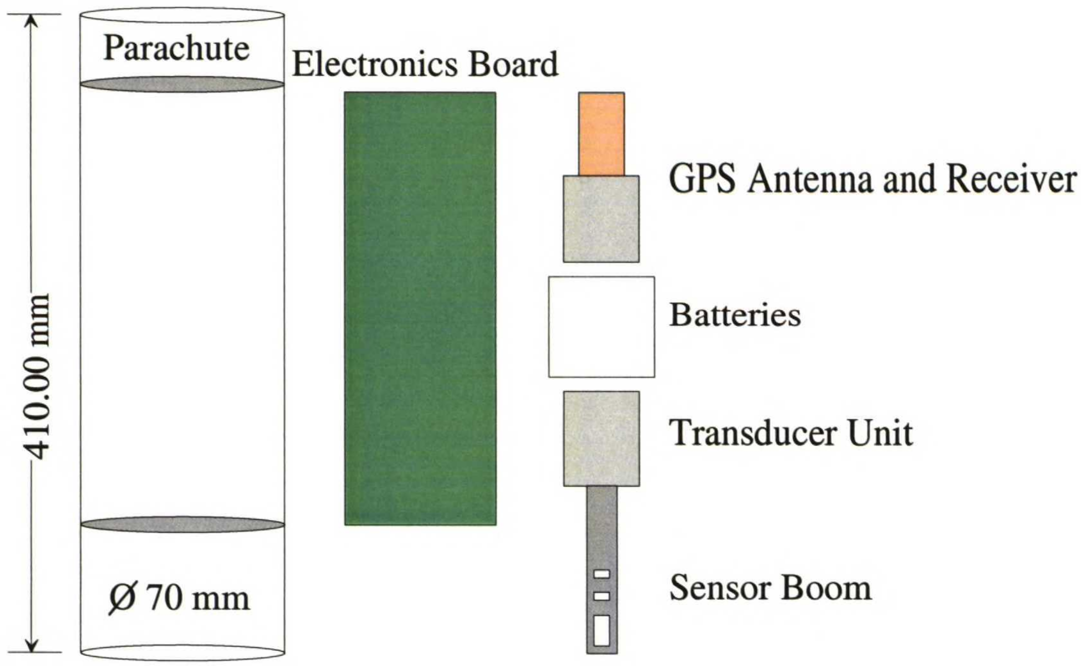


Figure 4. RD93 Interior Modules.

Manned airplanes with technicians to deploy the dropsonde form the platform from which these dropsondes are used. The platform itself consists of long tubular shaft through the hull of the aircraft with pressure valves on both ends. After the initial check-up and preparation, the dropsonde is placed into the shaft and the shaft closed. The second valve is then opened which releases the dropsonde into the atmosphere. Presently the receiving system is capable of tracking four dropsondes simultaneously and this receiving system is located in the aircraft. The receiving system AVAPS - Airborne Vertical Atmospheric Profiling System - consists of telemetry hardware, computer, monitor and printer and thus an entire AVAPS system takes a lot of space. *Figure 5* illustrates the launch conditions of RD93. The initial check is essential for two reasons - first to see that the dropsonde is operating as should and sending data to the receiving system and secondly to feed GPS data from external GPS antenna for the dropsonde to establish the location of deployment. After this is done the dropsonde is ready to be deployed through the launch tube. [3]

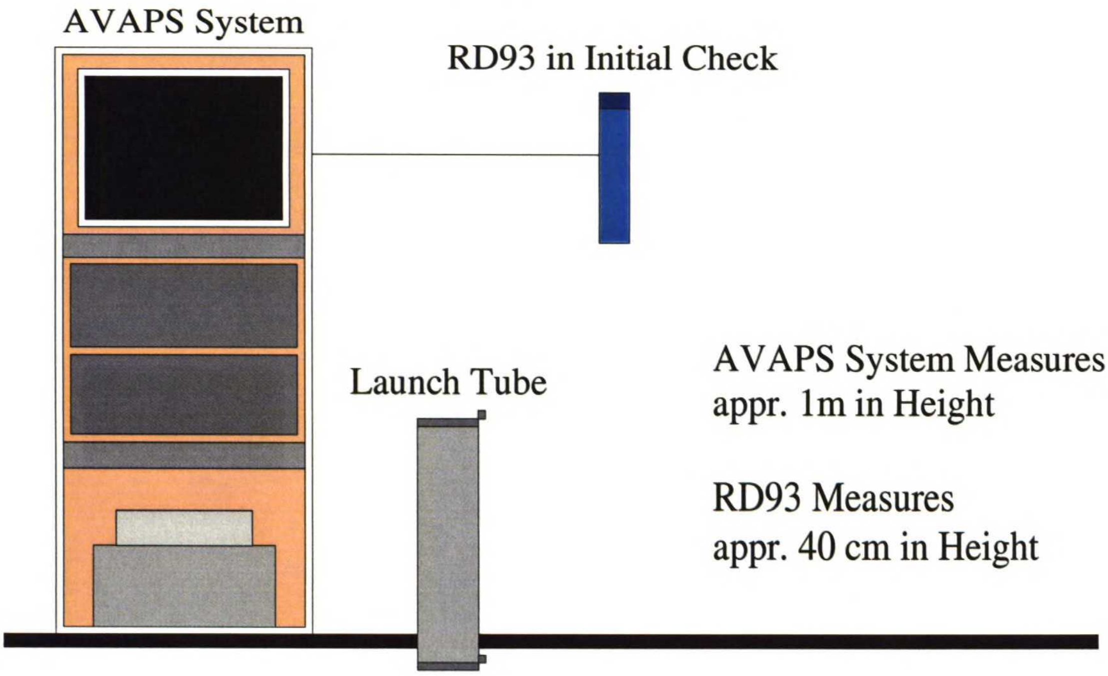


Figure 5. AVAPS System.

One RD93 dropsonde sounding - a drop from an airplane to the ground - lasts (depending on the altitude of the aircraft) approximately 15...20 minutes. In this time the dropsonde produces sensor readings twice per second for each sensor - temperature, humidity, pressure and wind solution. The sensor mechanics and operation is analyzed in more detail in the upcoming chapter. This chapter outlines the modules of the dropsonde to gain more understanding of the dropsonde.

3. MODULES OF DROPSONDE

The different modules that make up a dropsonde will be described in this chapter. The basic concept is quite similar between existing radiosondes and dropsondes. The modules inside these sounding devices are the same. Each has a power source, a measuring unit and a transmission unit to name a few. But an actual module however, differs. In this chapter each of the module will be described to gain understanding of the actual dropsonde package and to understand the requirements each module has to satisfy in order to function in an ICARUSS platform. These requirements are addressed in Chapter 6.

3.1 RD93 Dropsonde Modules

Figure 6 illustrates the RD93 dropsonde interior and shows the placing of the different modules. The figure shows the dropsonde from both sides, as the modules have been placed on either side of the main circuit board. The circuit board itself works as a mechanical structure for the whole dropsonde and all the modules have been attached to this board.

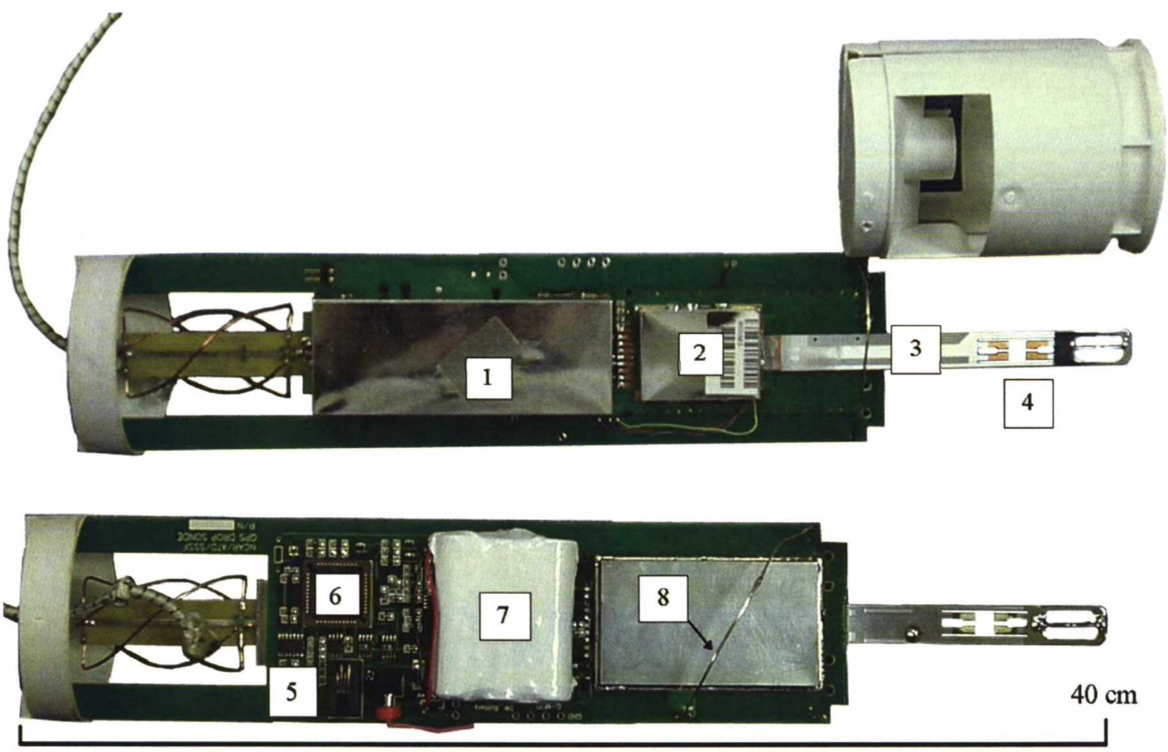


Figure 6. RD93 Modules.

The modules numbered in *Figure 6* are

1 GPS unit together with helix GPS antenna

2 Transducer unit

3 Sensor boom

4 Sensors

5 Ground check plug

6 Processor

7 Power source

8 Transmitter with the transmitter antenna indicated by an arrow

RD93 Technical data sheet is included in the Appendix **[A1]**

3.2 GPS Module

GPS - Global Positioning System - takes advantage of numerous satellites orbiting the Earth on a 12-hour orbit to produce navigation solution for terrestial observers. The GPS satellites send a continuous signal that can be used in receiving systems worldwide. This satellite signal consists of two carrier signals, whose frequencies are 1575.42 MHz and 1227.60 MHz. Two GPS code signals are also transmitted by the satellites, which include the information of the satellites and their position. By observing four satellites simultaneously, a three-dimensional position can be calculated - three satellites for three dimensions and one for time. [4]

The present day dropsonde uses GPS technology to produce a wind solution. The movement of the dropsonde indicates the wind properties. This solution includes the direction and the speed of the wind. The used technique is based on the Doppler shift of the transmitted GPS satellite signals and as such the present day GPS module does not use the GPS code. This module is preheated before the actual deployment of the dropsonde to establish satellite tracking and to ensure liable operation of the wind solution.

As seen in *Figure 6* the present day GPS module is large. This module alone takes about a half of the 40-cm length of the dropsonde and the GPS helix antenna takes a big portion of this. The helix antenna produces a mushroom shaped antenna gain pattern, and as it is located upwards with maximum gain in the zenith, it provides ideal gain pattern to receive GPS satellite data. The helix antenna gain pattern is included in the Appendix **[A2]**.

3.3 Transducer Unit

Transducer unit is the module that feeds the temperature, humidity and pressure sensors with an input signal and processes the sensor output reading to a form that can be directed to the transmitter. The transducer unit itself includes the pressure sensor inside the metal casing seen in *Figure 6.*

3.4 Sensor Boom and Sensors

The sensor boom is designed as a long 15-cm and narrow piece of electronics board to which the temperature and the humidity sensors are attached. The shape of the boom is designed to allow the sensors to be as far away from the heat producing elements of the dropsonde and to allow the sensors to measure undisturbed air while descending. The sensors themselves are located at the very end of the sensor boom, the temperature sensor being the outmost sensor and the two humidity sensors located after. The number of humidity sensors is two to allow melting of the accumulating ice on top of the sensors when the sensors are in an environment where this can occur. While the other sensor is being heated the other one measures and vice versa. The entire boom is coated with aluminum to minimize the radiation error to the sensors.

3.5 Plug-Ins

The RD93 dropsonde is equipped with a pre-launch check up plug, through which one ensures that the dropsonde is functional and ready for launch. Battery voltage and sensor reading together with the setting of transmission frequency can be read and fed from this plug and the dropsonde can also be fed with external power. The importance of plug-ins is to make sure that a functional dropsonde is deployed and that everything works before launch.

3.6 Power Source

Power source naturally provides the dropsonde its power required to perform a sounding. This includes the pre launch check up and the duration of one drop. RD93 dropsonde uses six 3 V lithium based batteries to provide the dropsonde the needed 18-Volt operation voltage. The pre-launch procedure uses 3.6 W of power, which require 200 mA of current from the power source. From this 100 mA is needed to heat the GPS module and 100 mA to apply the rest of the modules' power. Once the heating is done the total power need decreases to 2.9 W with 18 Volts. It is an important characteristic for the dropsonde to stop transmitting after a sounding has been made to avoid mixed signals with still measuring dropsondes. This can be done with the power source, which is drained after the time period of one sounding or with separate transmission killer.

3.7 Transmitter

The transmitter is used to send the sensor readings to the receiver. This information is transmitted with a carrier frequency, which can be set anywhere in the 400 MHz meteorological band - 400...406 MHz - in 20 kHz steps. The transmitter circuitry uses a crystal to produce the transmission frequency. The PTU - the sensor readings from **P**ressure, **T**emperature and h**U**midity - and the wind data are included in the transmission. The present RD93 transmission antenna is a simple dipole antenna, which is whirled around the tubular body of the dropsonde.

3.8 Parachute

The parachute reduces the rate of descent of the dropsonde to guarantee sufficient vertical data resolution and a descent, which "drops" the dropsonde rather than allowing it to glide down. As the sounding is a vertical profile measurement of the atmosphere, the preferred descent rate is thus by fully vertical motion. The wind however produces the horizontal component of the descent and as this element is one of the measured quantities, the parachute has to allow the dropsonde to be moved with the wind to measure the wind direction and strength. But as stated the parachute is not to allow the dropsonde to glide and thus create unwanted horizontal movement and error to the wind solution. The present RD93 parachute is a square-coned shaped, ram air filled parachute, which produces the described descent for the dropsonde.

4. HIGH ALTITUDE PLATFORM

A platform used by dropsondes distinguishes a dropsonde from a radiosonde. A balloon works as a platform for radiosonde whereas a dropsonde is planned to take advantage of numerous different platforms. This chapter describes the different platforms that are designed for future use - HAPs (High Altitude Platforms). First we are going to look at the reasons behind this arising need for new platforms and then individually describe the designed platforms.

4.1 Need for New Platforms

Meteorological study and predictions rely heavily on synoptic data, which is collected throughout the world. Synoptic measurements are conducted continuously at specific locations and times. This is done with the help of radiosonde soundings from fixed sounding stations around the world. This data is used together with weather satellite data to come up with a specific atmospheric model for certain time period. *Figure 7* demonstrates the fixed sounding stations around the world. The horizontal axis represents the longitude and the vertical axis the latitude of Earth.

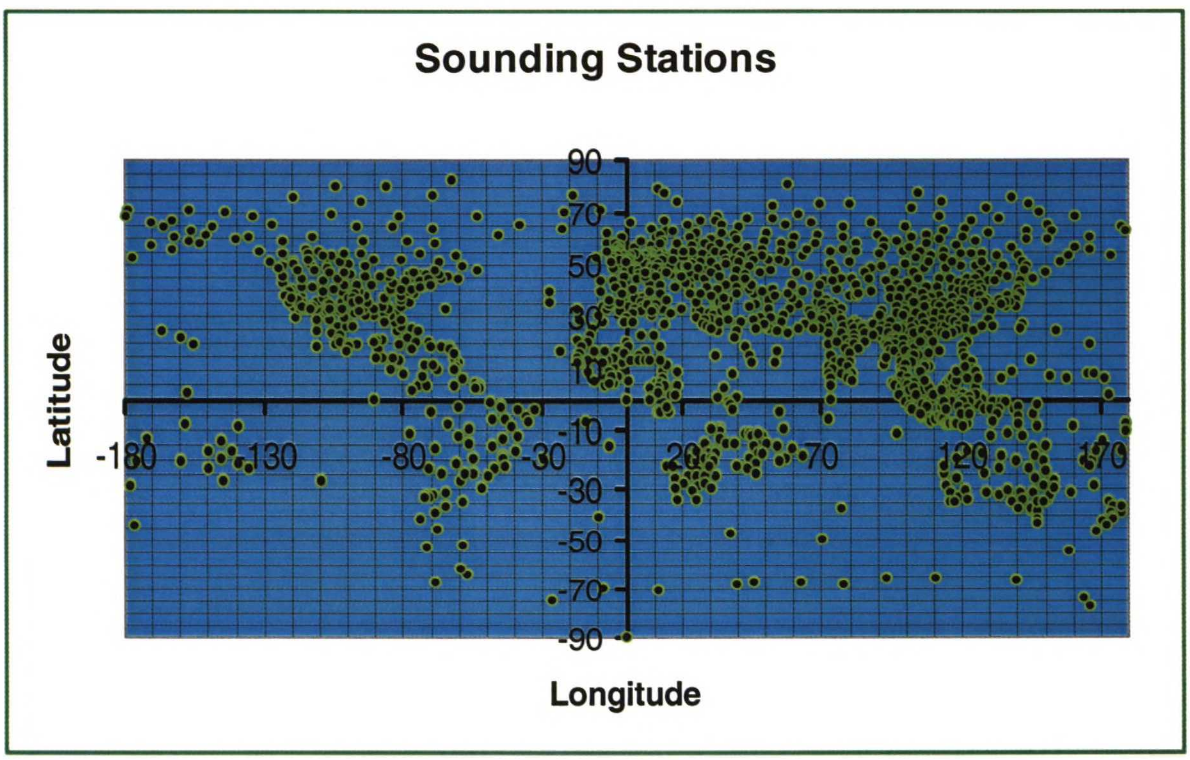


Figure 7. Sounding Stations Around the World.

As *Figure 7* illustrates, the sounding stations are quite densely placed in the Northern Hemisphere continents of North America, Europe and Asia, but one striking detail can be seen from the figure. There are huge spaces void of any sounding stations. These areas include all the seaboards - Pacific, Atlantic, and Indian Ocean to name a few - as well as continental areas such as the vast desert of Sahara and desolate places such as Siberia. Also the entire Southern Hemisphere lacks dense sounding grid. Atmospheric data from these areas is thus collected solely by weather satellites, which cannot produce as accurate data as radiosondes. This situation concerns researchers and communities alike.

Discussions with atmospheric experts indicated that regular measurements from oceans are very rare indeed [5] and that dropsondes have an important role not only acquiring this data but to validate weather satellite data and to improve the operational weather forecast cycle [6]. Furthermore the use of dropsondes in specific targeted observations over some discreet weather phenomenon is encouraged [7].

Most factors that affect the weather are formed in oceans. Ocean currents move massive amounts of heat and create variable conditions all around the world. [8][9] Thus it is imperative to gather data from these data sparse regions indicated in *Figure 7* to get much more reliable and accurate models of the atmosphere. The ways to do this have existed for a long time, but ways to conduct it cost efficiently have not. This setting has given rise to numerous international projects that seek to find an answer to this dilemma. The question has been "how to perform synoptic measurement in these areas cost efficiently" and the answers have recently been focused on "what kind of platform is needed for a dropsonde". It has thus been noted that a dropsonde is the only accurate - by far - reliable and economically viable way to solve this problem. These different international projects have come up with different solutions and most of them rely on the use of dropsondes as the measurement instrument. Other instruments include onboard sensors, which operate for much longer periods of time. [2]

These new fields of use for a dropsonde are the reason why the existing RD93 dropsonde has to have a successor. The operational surroundings differ greatly in comparison to the present day platform of a manned aircraft and if the reliability and accuracy of the measurements is to be kept at the same level or even better, major changes has to be made to the design of the next generation dropsonde.

Next we are to look at various projects that have been initialized internationally and look at the conditions they would expose the dropsondes to. The next chapter focuses entirely on one of these international projects and from that project's demands we start to derive the requirements for the next generation dropsonde.

4.2 THORPEX Project

THORPEX - The Hemispheric Observing System Research and Predictability Experiment - is one of the international projects that have envisioned the use of dropsondes with different platforms. The project itself identifies five different ways to obtain meteorological data from data sparse areas and two of them rely on the use of dropsondes.

4.2.1 THORPEX Project Background

The forecasts obtained today from the fixed stations located around the world - *Figure 7* - and from weather satellites have not been able to predict the weather conditions sufficiently accurately. That is, the forecast has not been able to produce accurate approximation of the weather patterns. The reasons for this often arise from poorly defined initial conditions in data sparse areas. Extreme weather conditions, such as snowstorms and hurricanes can cause extreme damage to societies and individuals and thus the prediction of these weather phenomenons is an important factor. Studies have shown that the largest 72 hour synoptic - local - scale forecast errors in The United States during January and February of 1997 to 1999 can be traced to poor upper-air analyses of temperature and wind over North Pacific Basin and Arctic North America. Similarly for Europe the errors have been traced to poor initial conditions over Canada. Studies have shown that these errors and the places that these errors are initialized vary greatly. This was demonstrated with the study of the weather phenomenon of El Niño and La Niña. The study demonstrated that the errors in weather predictions were far less in the El Niño year of 1998 than La Niña year of 1999. Different observing programs, such as FASTEX, NORPEX and WSR have further demonstrated that short and medium range forecast errors can greatly be reduced by the use of high quality dropsonde data in these data sparse areas. This situation has lead to formation of the THOPREX project. [2]

4.2.2 THORPEX Project Goals

The goals for the project are to obtain data from data sparse areas accurately and cost-efficiently. The hypothesis that the project tries to verify is that 2 to 10 day weather forecasts can be improved significally by collecting this data. The project has envisioned five different plans to gather data from these regions. The project also includes the study of regions where the observations would be most efficient and suggests concrete measures how the measurements should be conducted in the form of different dropsonde platforms and other weather instruments. [2]

4.2.3 In-Situ Observing Systems

THORPEX has envisioned five observation systems to collect data from the areas that lack permanent instrumentation. These systems will be addressed here individually and studied in relation to the dropsonde application.

4.2.3.1 DriftSonde

This application is designed to provide coverage for seaboards and large remote continental areas through the use of dropsondes. The platform designed for the dropsondes is attached to a constant level balloon that will cruise in the prevailing upper atmospheric winds at altitudes of approximately 20 km and deploy dropsondes at regular intervals. The dropsondes then measure a vertical synoptic measurement from the place of deployment. This application is studied in more detail in Chapter 5 as the ICARUSS project focuses on this application solely. [2]

4.2.3.2 AeroSonde

AeroSonde application is designed to obtain data from seaboard areas through ascending and descending while travelling. The idea behind the AeroSonde is to release this balloon carried measurement device from coastal regions and let it be carried in the direction of the prevailing winds. At the same time the sonde is allowed to ascend to its maximum altitude of about 5 km and then allowing it to descend to sea-level altitudes. This cycle is then repeated. Constant measurement of the atmosphere is applied throughout the flight. The data collected by the AeroSonde will be transmitted to a LEO - Low Earth Orbit - satellite and from there on to a ground station.

The challenge of AeroSonde is to overcome the problem of icing as the sonde varies its altitude and encounters different weather conditions as well as proper communication to ensure safe commercial air traffic in the area of operation. The plans are to test the system with five to ten AeroSondes released from Hawaii in 2001. [2]

4.2.3.3 Ocean Surface Data Buoy

Data buoys are planned to be placed at fixed locations in oceans and to measure the sea level conditions continuously. The application is planned to have an operational time of 2 to 3 years. This platform could be implemented together with the Weather-Rocket Buoy System described next. [2]

4.2.3.4 Weather-Rocket Buoy System

A network of these floating buoys placed at desired locations are designed to house a number of RocketSondes, which could be launched on a daily basis to altitude of about 8 km. There the rocket would deploy its payload dropsonde and the dropsonde would measure the vertical in-situ profile of the atmosphere. Vaisala is currently manufacturing RocketSondes for lower altitudes of about 1 km, and the dropsonde payload used in this application would provide a solid basis for the future high altitude RocketSonde. The exception being that Vaisala's present RocketSonde does not measure winds, which would have to be installed into the Weather-Rocket Buoy System. [2]

4.2.3.5 Constant Pressure Level Drifting Balloon

Again relying on helium or hydrogen filled balloons, this Constant Pressure Level Drifting Balloon is designed to include several balloons with attached measurement devices that cruise in the atmosphere at certain pressure levels. Pressure present in the atmosphere is a function of altitude. Pressure reduces at higher altitudes but discrete differences in the pressure levels occur in different altitudes in the atmosphere. Generally this means that certain pressure levels, for example 500-hPa level, will fluctuate around 5000 meters. The amount of fluctuation is dependent of the atmospheric conditions. These balloons would thus be set to different pressure levels - generally to different altitudes - and to remain there and measure the atmosphere. This way, data could be gathered on different horizontal layers instead of vertical profiles provided by dropsonde systems. The reasoning behind this approach is that it is not yet established which observation procedure reduces the errors in weather predictions the most or that can they be discriminated. Thus both vertical observation by dropsondes and horizontal observation by constant pressure level balloons are included in the THORPEX program. *Figure 8* illustrates the different systems envisioned in the THORPEX plan and indicates the dropsonde platforms. [2]

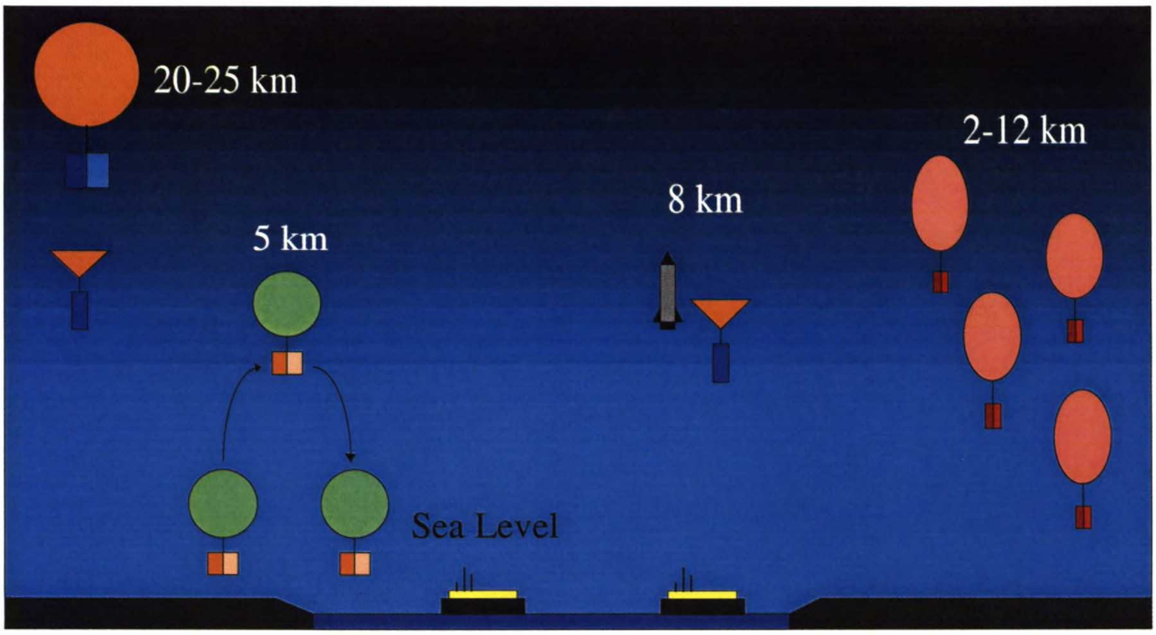


Figure 8. THORPEX Project In-Situ Observing Systems.

4.2.4 THORPEX Project's Dropsonde Platforms

As indicated, the planned THORPEX Project's observing systems use two different platforms for dropsondes - one for DriftSonde application and the other for Weather Rocket application. The DriftSonde application has been the most promising application. Projects predating THORPEX have studied the use of DriftSonde-like observation systems and the use has been verified through field tests. This platform is thus considered the most likely to emerge for commercial use and the first prototype series for the next generation dropsonde will be designed for this high altitude platform. The Weather Rocket system would use model rocket as a platform for the dropsonde and this will set yet more requirements for the dropsonde to be used. This however is outside the scope of this thesis.

4.3 GAINS Project

The GAINS - Global Air-Ocean In-Situ System - follows the same principles as the THORPEX Project. The main goal of the project is to increase in-situ measurements in data sparse areas, mainly the seaboards, with the use of dropsondes. The reasoning behind the project is derived from similar sources that have indicated that data needs to be gathered from these uncharted regions. The GAINS project has dedicated its resources for one application only and this has undoubtedly made the project more efficient and focused. [1]

4.3.1 GAINS Background

The GAINS Project dates back to 1995 when Forecast Systems Laboratory of the National Oceanic and Atmospheric Administration (USA) started a similar project to gather data from data sparse regions with the help of a balloon. This project was abandoned due to difficult engineering problems and aviation safety regulations, since the balloon - AeroSonde alike- was designed to travel between 50 meters and 11-km altitudes on regular basis. The GAINS Project adapted a slightly different approach and introduced the idea of high altitude superpressure balloon, which would operate in altitudes of 18 to 23 km instead of going up and down. The construction - very much like THORPEX Projects DriftSonde - would however have an operational lifetime of one year instead of DriftSondes designed operation lifetime of few days. This approach further differentiates the requirements that have to be taken into consideration not only in the platform itself, but also in the used dropsondes as well. [1]

4.3.2 GAINS Project Overview

The GAINS Project targets to place around 400 units of superpressure balloons, measuring 37 meters in diameter, capable of carrying up to 350-kg payloads to altitudes of 18 to 23 kilometers above areas void of weather instruments. These balloon carried payloads would house a supply of dropsondes to last the designed operational lifetime of one year. The safety issues concerning the project have been well identified to avoid similar difficulties to arise as what occurred with Forecast Systems Laboratory design. Active safety measures include GPS technology, which is implemented on the platform itself to obtain real-time data of the locations of the balloons and feed this information further to aviation authorities. The balloon can also be landed safely if the need arises by independently lowering the balloon at desired time. Passive safety measures include the operational altitude which is above all commercial aviation and other activity and the balloon resides in hazardous airspace only two times during its operation - on the way up and consequently on the way down. Frangibility - object's ability to break into small pieces - has been implemented on the dropsonde requirements. This is to reduce the risk of damage upon impact on other objects. However through the lifetime of dropsondes and more especially radiosondes, which fall from the sky after their balloon burst, critical damage has not occurred to people or to property. As these dropsondes are deployed over seas and other desolate places, the probability of damage occurring of parachute-equipped dropsonde is practically null. [1]

4.3.3 GAINS Platform

Figure 9 illustrates the GAINS platform and its key parts. The balloon is a three-layer construction with Spectra™ envelope as an outer shell under which a layer of air is filled.

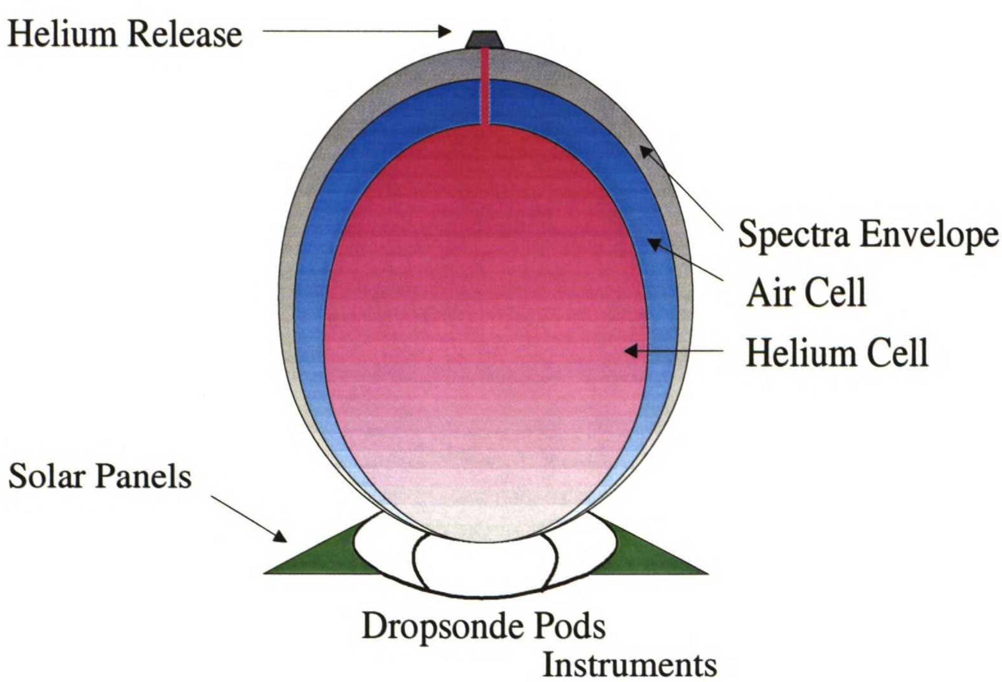


Figure 9. GAINS Superpressure Balloon.

The helium is stored under the air layer and equipped with a release valve to control the altitude. The dropsonde pods are located at the bottom together with the systems instruments and batteries. The testing and promotion of GAINS superpressure balloon platform has included different sized balloons capable of carrying less weight to lower altitudes, but for testing purposes this has been proven adequate. The GAINS platforms are designed to operate at low latitude regions as well as polar caps and Southern oceans. The testing sessions have verified the operation of the GAINS balloon and further tests are aimed for the future to test primarily the reliability and general operation of the platform. The project aims for full operational readiness by the year 2006. [1]

4.4 UAV and Aircraft Platforms

UAVs - Unmanned Air Vehicles - and aircraft platforms come in many different forms. The range of platforms includes slow moving, high altitude unmanned air vehicles and jet aircrafts flying in low altitudes with considerable velocity. This situation obviously sets the dropsonde qualities to be application specific.

4.4.1 Dropsonde in UAV and Aircraft Platforms

The use of dropsondes with aircraft platform is the only present platform used for dropsonde application, if neglecting the low altitude RocketSonde manufactured by Vaisala. Vaisala's present dropsonde RD93 is solely used from aircraft as described in Chapter 2. This allows the dropsonde to reside in a controlled environment prior to deployment but the velocity of the aircraft demands that the deployment impact should not be too severe to damage the dropsonde. Typical airspeed for RD93 platform aircraft is around 300 knots.

UAVs lack an operator handling the dropsonde prior to deployment and generally the velocities of UAVs are lower making the deployment subtler. UAVs are mainly used for military purposes and the range of measurement environments varies depending on the UAVs nature. NASA's ERAST program - Environmental Research And Sensor Technology - concentrates on different UAV platforms for numerous different tasks from scientific observations to commercial data link use. [10] Dropsonde system in these applications would present an ideal weather measurement application. To conclude the different types of UAVs, the planned platform usage environment has to be well established prior to assigning a dropsonde for its use.

4.5 Platform Summary

When studying the different platforms planned for dropsonde use, three major factors that differentiate them can be identified,

- The velocity at which the platform is travelling
- The altitude the platform is residing
- The operational lifetime of the platform

These three factors make up the characteristics of a certain platform and thus set the requirements for the dropsonde. Each factor includes different set of sub-factors that further differentiate the platform from others. For example the altitude of the platform creates different environment temperature- and pressure-wise. To understand these factors, further analysis has to be made

4.5.1 Platform Velocity

DriftSonde and fast moving jet aircraft platforms represent the two extremes velocity-wise. DriftSonde application moves together with the prevailing winds, whereas aircraft always has a velocity greater than this. Primarily this motion of the platform makes the dropsonde more vulnerable upon deployment due to the wind drag caused by the motion. The more speed the platform has the more of a shock it will be for the dropsonde after deployment.

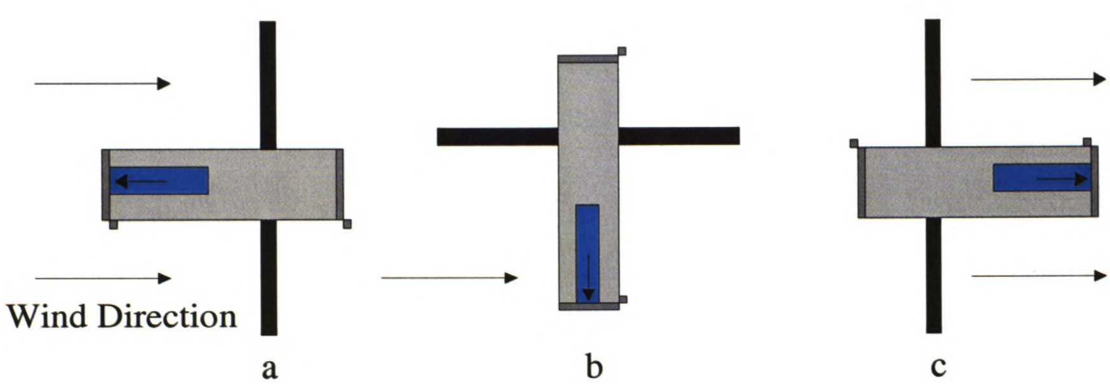


Figure 10. Launch Tube Orientations.

This shock or sudden impact with air can cause significant damage to the dropsonde and especially to the sensors standing outside the body of the dropsonde. This fact has to be accounted for when designing the dropsonde. As the speed of the platform is set, the only way to influence the impact the dropsonde experiences is to focus on the exit of the dropsonde.

The direction of the deployment in relation to the wind whirling outside the platform has to be optimized - *Figure 10*. Launching the dropsonde against the airflow - *Figure 10a* practically impossible - would create an extreme shock to the dropsonde. Perpendicular deployment - *Figure 10b* - also creates a significant shock. By deploying the dropsonde in the direction of the airflow - *Figure 10c* - the impact of the wind can be reduced to minimum. In reality this would mean a tilted launch tube instead of horizontal tube at the back of the aircraft, due to the difficulties of placing the tube at the very end of the aircraft. Also the turbulence caused by the aircraft might pull horizontally deployed dropsonde upwards and risk hitting the aircraft rear parts. After exiting the launch tube the sonde experiences the first initial shock and a deploying parachute causes the second shock. This shock can be reduced if the actual velocity - horizontal velocity - of the dropsonde can be reduced to minimum. This can be achieved by delaying the parachute deployment and allowing the dropsonde to minimize its horizontal velocity component. Given the DriftSonde type platform, which moves with the prevailing winds, and thus sets the deployment of the dropsonde completely different. A vertical deployment - *Figure 10b* - can and should be used since the dropsonde does not meet heavy wind drag. Furthermore the deployment of the dropsonde's parachute should be immediately after the dropsonde is released to ensure proper descent rate at the very beginning of the sounding.

This comparison of the platform velocity differentiates the dropsonde design to be platform specific and concentrates on the direction of the deployment and the delay time of the parachute deployment.

4.5.2 Platform Altitude

The altitude of the platform affects many factors in the design of the dropsonde. As mentioned temperature and pressure as well as wind conditions change as a function of altitude and this sets their own requirements from the dropsonde design. Temperature control of the dropsonde becomes an important factor when the altitudes of operation start to approach 5 to 10 kilometers. The temperature at these altitudes is significantly lower than at sea level and long periods in these kind of conditions effect the dropsonde. Furthermore the density of air decreases at higher altitudes and thus affects the rate of descent of the dropsonde. The parachute creates less wind drag and thus descents faster at higher altitudes. Chapter 6 focuses on the DriftSonde type ICARUSS platform dropsonde and this issue is dealt there in detail.

4.5.3 Platform Operational Lifetime

One of the major challenges in designing a next generation dropsonde is the operational lifetime factor. The present dropsonde RD93 has an operational lifetime around few hours - the time it is checked and made ready and the drop itself. This would not be the setting with THORPEX or GAINS like platforms. GAINS superpressure balloons have a lifetime of one year and this would be the time the dropsonde should remain operational. Though not in use through the whole one year time period, the "sleep-phase" of the dropsonde still set some challenging requirements for the dropsonde. Mainly the concern focuses on the reliability of the sensors and how well they can be protected through this time period to measure accurately when the time comes. Again the temperature control of the dropsonde changes as the operational time changes and adds to the variables of design factors. As this thesis focuses on designing a dropsonde for DriftSonde type ICARUSS platform, where the maximum time of exposure to extreme environment is one week, the GAINS like platforms remain outside the scope of the thesis.

As stated, the next chapter focuses entirely on the ICARUSS platform where each of these platform factors are examined in detail. Other kind of platforms are out of this thesis' scope and thus not addressed here, but it is imperative to be aware of these different factors in different platforms and how they direct the development process of a dropsonde. Ultimately the development of this next generation dropsonde will include all possible platforms - from slow moving to rocket platforms and from high altitude to low altitude ones.

5. ICARUSS PLATFORM

The ICARUSS - Inter-Continental Atmospheric Radiosonde Upper Air Sounding System - is a separate project focusing on designing an operational solution for THORPEX Project's envisioned DriftSonde application described in Chapter 4. In this chapter the general operation of the ICARUSS platform is examined. The study of the environment the platform operates in will follow next. This is followed by the thermal analysis of the environment and the platform to understand the conditions in which the dropsondes have to reside.

5.1 ICARUSS platform in General

As described in Chapter 4 the ICARUSS platform consists of helium filled balloon and a payload, called gondola. *Figure 11* illustrates the system.

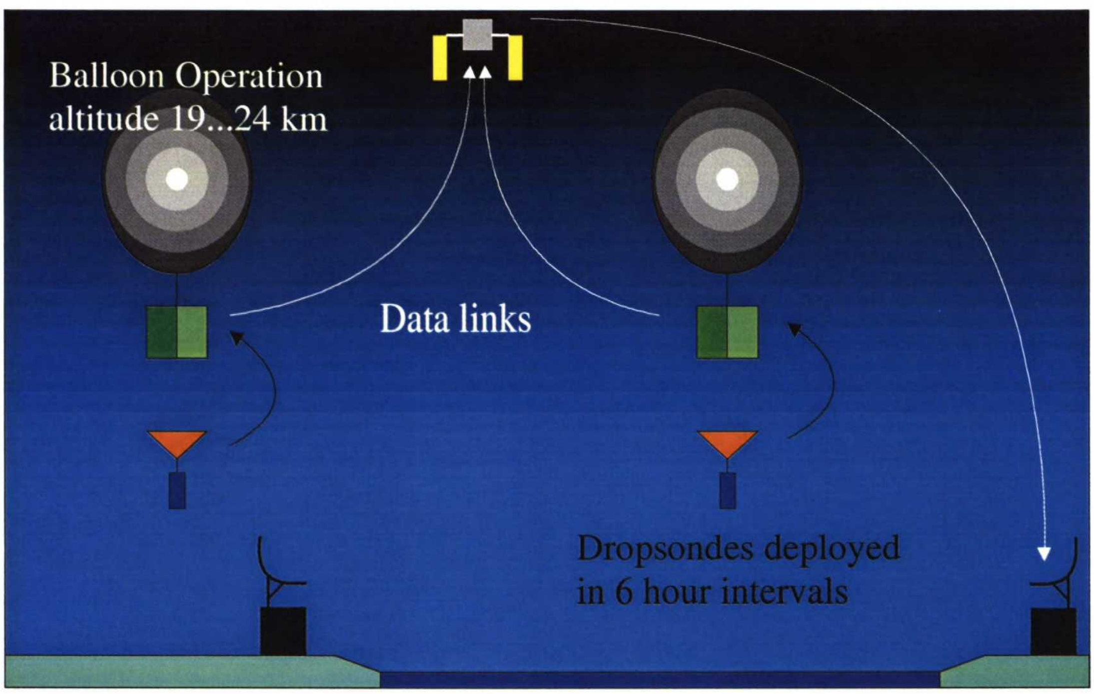


Figure 11. ICARUSS Platform.

The operation altitude is set between pressure levels of 100 and 50 hPa corresponding to 19 to 24 km (*Note - some average atmosphere models set these pressure levels to altitudes of 16 to 21 km).* The gondola is designed to house 24 dropsondes, which are released in 6-hour intervals according to the sounding station time frames. The data gathered by the dropsonde is sent up to the gondola and the gondola transmits this data to a LEO satellite, which in turn sends the data to a ground station for further analysis. This setting allows the platform to conduct soundings for a time period of 6 days over the areas it moves. Few simulations have been conducted to study the path of the balloon-gondola system and they have showed that platforms launched from Pacific coastal regions - both US side and Asia side - will take the platform over the Pacific in 5 to 6 days - some simulations predict even 3 day journeys. With a new balloon launched every 12 hours and each of these balloon-gondola systems deploying dropsondes in 6-hour intervals, the first four set of platforms will distribute their soundings as illustrated in *Figure 12.* [11]

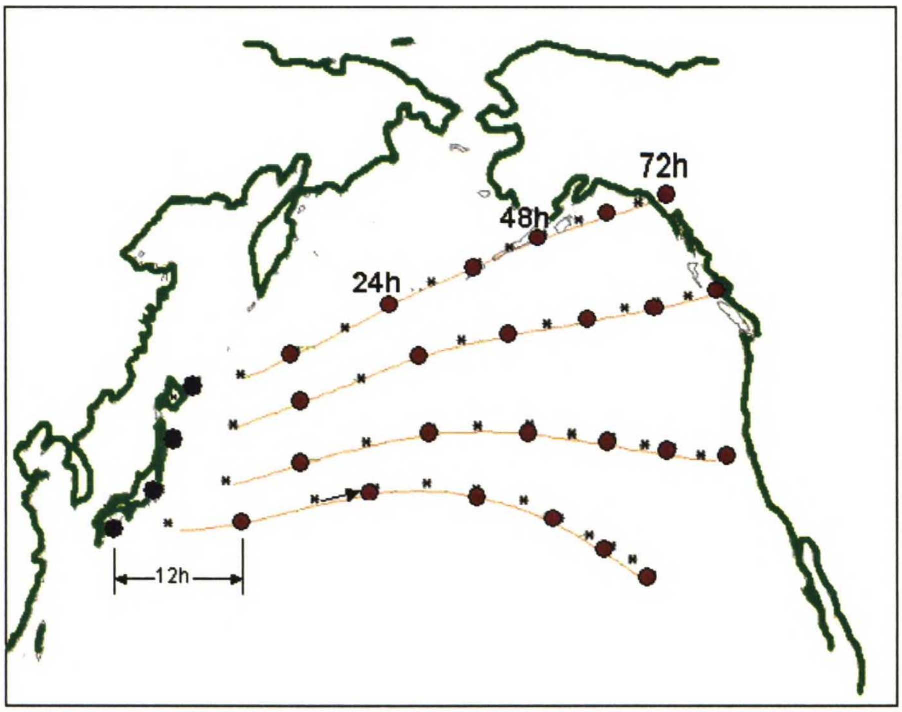


Figure 12. Simulated Paths for ICARUSS Platform over Pacific Ocean. [11]

The separation of the individual platforms remains quite good through the overseas journey. More launches would naturally make the grid denser and allow more soundings to take place. The platform is designed to be used in Northern Hemisphere over Atlantic and Pacific Oceans, where the prevailing wind conditions are proven to be most adequate for the application. [11]

The described dropsonde carrier - the gondola - is designed to carry 24 dropsondes, electronics to process the data sent by a dropsonde, ballast control and weights, communication hardware with a satellite and a power supply. The ballast is needed to maintain the desired altitude due to the fact that during night-times the helium contracts and decreases the volume of the balloon. By dropping ballast from the gondola the altitude can be maintained. The gondola is insulated and covered with black surface to optimize the thermal balance of the gondola as seen later in the thermal analysis of the platform. The helium filled balloon is made out of thin polyethylene film with a volume of 268 m^3. This balloon is capable of producing lift for 40-kg gondola, which windows the lift off capacity quite extensively. The gondola is designed to be single-use application. That is, once all the dropsondes have been deployed, the gondola is allowed to descend. [11]

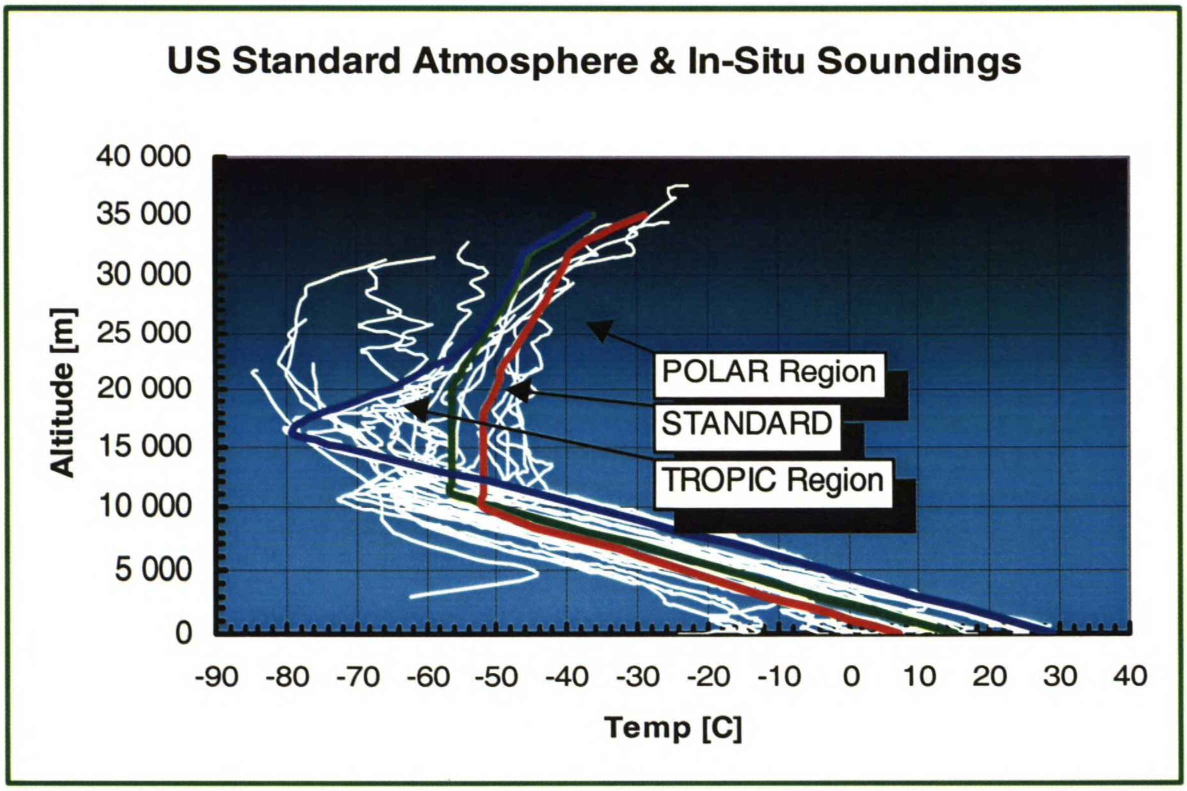
The present - summer 2001 - status of the ICARUSS project has begun to test the prototype platforms. Few test flights have been conducted, mainly test the communication links and thermal design of the platform and the initial results have verified the theoretical models. More testing sessions are scheduled for future dates to further examine the platform.

5.2 Analysis of the Operation Environment

The planned operation environment is set between pressure levels of 100 and 50 hPa. This around 20-kilometer environment creates an extreme condition for the platform to operate in and this influences the operation of the dropsonde itself. Next we are going to study this environment in detail and derive requirements for the next generation dropsonde for the ICARUSS platform.

5.2.1 Atmospheric Model

As a whole, the atmosphere is constantly changing and living. Generally the factors, temperature, density and pressure, follow a certain average values in proportion to the altitude observed. Thus in certain altitude we can predict to have certain average values for these factors. One of these average models of representing our atmosphere is the US Standard Atmosphere 1962 [12]. The figures given in this model are long time averages, and major differences can and will occur in same altitude in different places over the world. This of course is the one reason synoptic measurements are conducted - to detect the present values at specific places. But we do get a good approximation on how these factors change and interact in respect to the altitude with these models. *Figure 13* contains the graphical presentations of temperature and pressure in relation to altitude according to US Standard Atmosphere 1962 [11][12] - density is included in the Appendix **[A3]**. Temperature graph includes three average curves for tropic (blue), polar (red) and standard (green) areas and synoptic data gathered in June 2001 in different latitudes of the world.



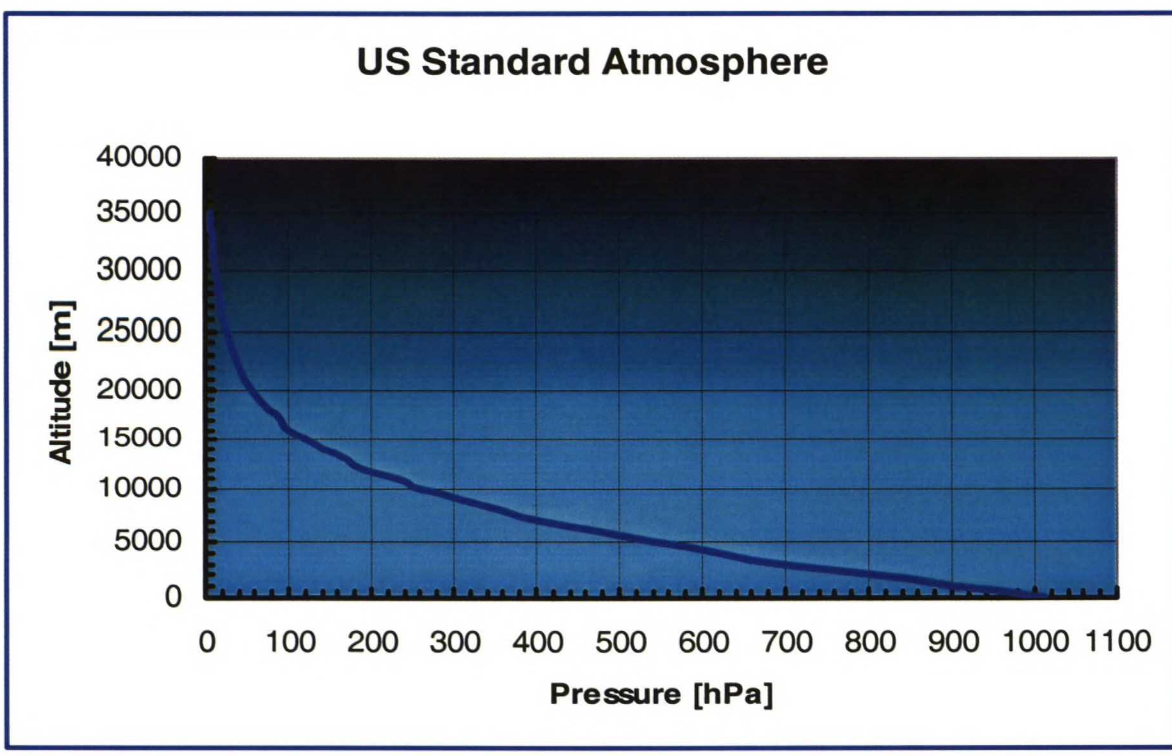


Figure 13. US Standard Atmosphere - Temperature and Pressure. [11][12]

Windowing the operation altitude of 16-21 km from the graphs, following average atmospheric values can be set for ICARUSS platform.

- Temperature range -45°C...-70°C
- Pressure 100 hPa...50 hPa
- Air Density 0.17 kgm^{-3}...0.09 kgm^{-3} (14...7 % of sealevel) **[A3]**

The environment at these altitudes is thus much more extreme than at lower altitudes. The temperature range can be expected to exceed above values. As seen from the graphs, the coldest region of the atmosphere is just above the tropopause - located around 11-km. Tropopause is defined as the height at which the lapse reduces to 2K/km or lower. The Standard Atmosphere model for Tropic indicates the coldest point at almost 16 km with temperatures of -80°C. Discussions with meteorological experts indicate that tropopause temperatures can reach as low as -90°C and that -80°C temperatures are common in tropics. Even tough the operational altitude is above the tropopause altitudes and thus the temperatures are warmer, the possibility of the ICARUSS platform experiencing these extreme cold temperatures must be kept in mind. Testing of the dropsonde has to include these conditions in order to study the behavior in case these conditions are encountered.

The lack of air leads to a situation, where the heat transfer of the platform is provided almost solely by radiation and since the platform is travelling together with the prevailing winds, practically no ventilation is present. Sudden gasps and turbulence can ventilate the system, but their duration in comparison to the operational lifetime is so insignificant that their effect can be ignored. The lack of dense air and low pressure - and cold temperature of the air - reduces the humidity to zero making the air completely dry and pure of contaminants. This has a good effect on the purity of the sensors and other components. Moreover the lack of water vapor prevents freezing from occurring at various parts of the system but the humidity trapped inside the system prior to the platform launch can cause some concern. These issues are dealt in Chapter 6. [9][12]

Given the planned operation time of 6-10 days, the gondola must be operational at all times during this time interval. During its journey it has to maintain operation during daytime as well as during night-time. These two separate cases contribute to the extremes of its operational environment. Let us next examine these conditions separately.

5.2.2 Daytime Conditions

During daytime flight, the Sun warms the gondola-balloon system. As discussed, the atmospheric density at these flight levels is small in comparison to the sea level densities, which leads to a situation, where almost all the heat is transferred through radiation. This means that the Sun's radiation is the primary heat source and it is responsible for applying the system it's thermal energy.

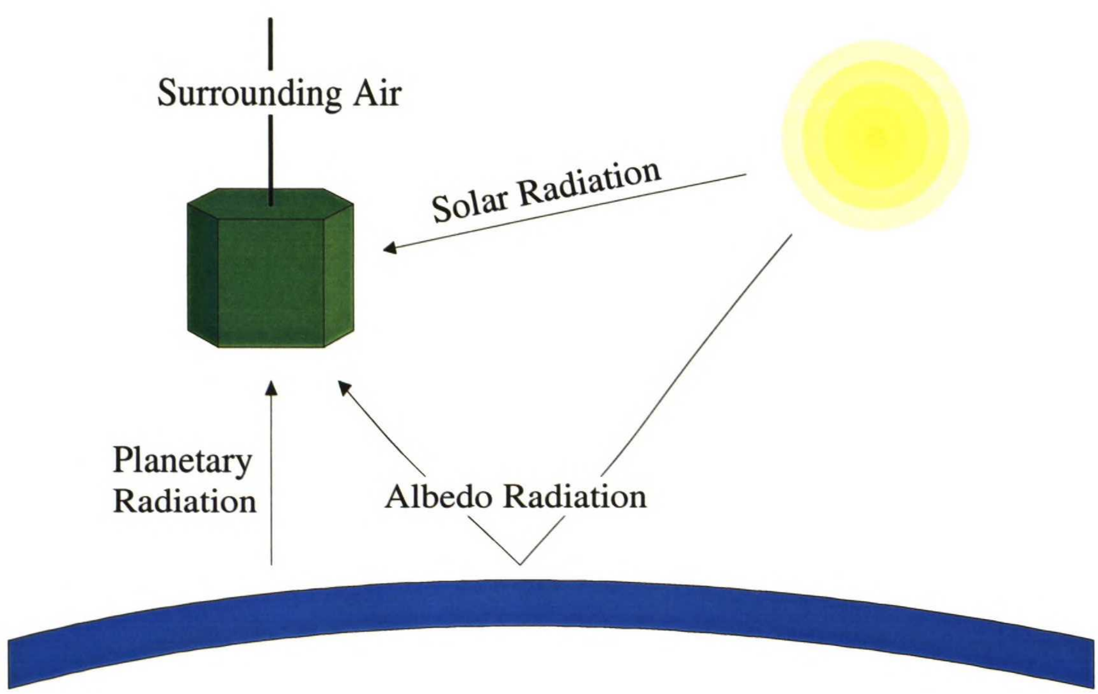


Figure 14. Heat Sources on ICARUSS Gondola.

In addition, we have to take into account the effects of the surrounding air, the Earth's albedo radiation and the planetary radiation as seen in *Figure 14* as well as the heat generated by the gondola's parts themselves. Together, these factors supply the system with thermal energy and set the system to specific thermodynamic level. Let us next examine each of these sources of heat. [14]

5.2.2.1 Solar Radiation

Solar radiation is the principal factor of heat producing elements in this system. The radiated power sent from the Sun decreases as the radiation travels through space interpreted with the following equation [14]

$$I_S = \frac{P}{4\pi r^2} \qquad (1)$$

I_S = Solar radiation intensity [Wm^{-2}]
P = Sun's total power output = $3.8 * 10^{26}$ W
r = Distance from the Sun

At Earth's distance away (1AU = 149 597 870 km) the radiation intensity is approximately 1350 Wm^{-2}. This value fluctuates but this figure serves as a realistic approximation. The spectral distribution of solar radiation resembles that of a 5800 K black body curve. This implies that almost all of the radiated energy - 99 % - lies between 150 nm and 10 μm with the maximum approximately on 450 nm. The atmosphere absorps Solar radiation and the intensity of the radiation is a function of elevation angle and pressure. This incident angle illustrated in *Figure 15* by case 1 and 2 determines the amount of radiation received. At low incident angles - case 1 - the Sun is close to the horizon and the atmosphere absorbs much of the radiation due to more air on the path - x_l - of the radiation. At higher incident angles - case 2 - the Sun's radiation gets through more efficiently especially at high altitudes where the radiation does not have to travel through thick layers of air - marked x_s. The intensity of the radiation can be calculated with *Equation 2.*

$$I = 1.12 \times (1 + 0.2665x)^{-0.325} - (0.0011\sqrt{x})^{-0.11}$$
$$x = \frac{0.003p^{1.57}}{E+1} \qquad (2)$$

where I is the intensity, p pressure and E incident angle.

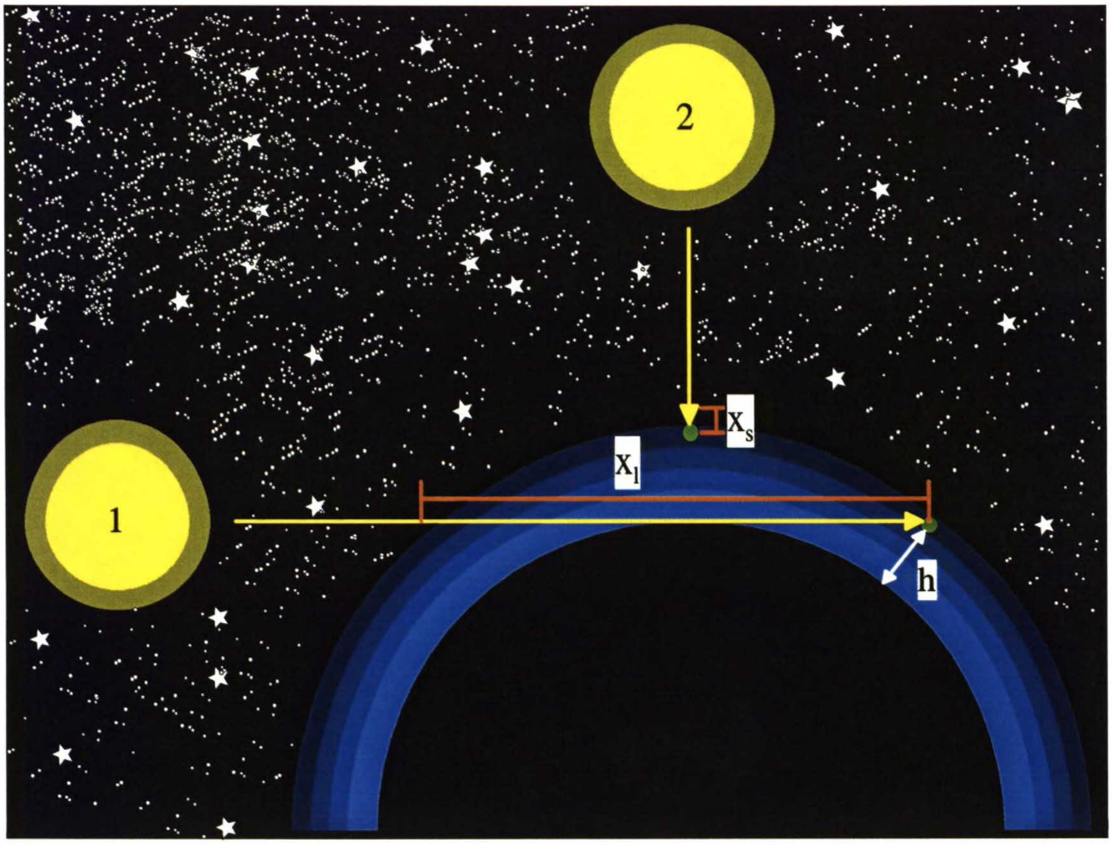


Figure 15. Solar Radiation Received in Relation to Incident Angle.

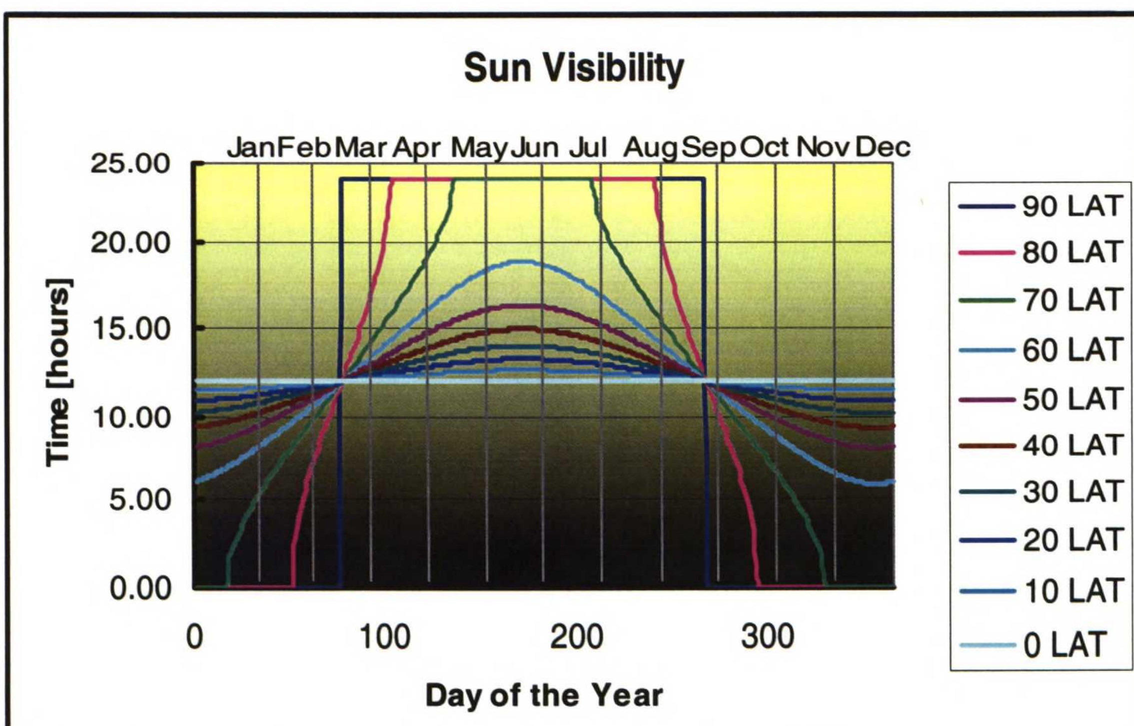


Figure 16. Sun Visibility in Relation to Latitude and Time. [15]

Figure 16 illustrates different time periods for each month of sunrise and sunset in relation to the latitude of the observer in the Northern Hemisphere. The figure shows clearly that the time when the Sun is above the horizon varies greatly in relation to the latitude of the observer and the time of the year. Polar regions receive 24 hours of Sunlight per day during northern summer months and in relation receive none during northern winter months. Equatorial regions on the other hand receive constantly close to 12 hours of Sunlight per day. Southern Hemisphere receives similar amounts of Solar radiation but in inverse amounts. Southpole receives 24 hours of Sunlight during northern winter months and none during northern summer months. [15]

5.2.2.2 Albedo Radiation

The proportion of Sun's radiation, which is reflected back to space from different objects on Earth, is called the albedo radiation. Thus, when an observer observes the Earth from outer space, he can see only albedo radiation reflecting from the Earth. This reflected albedo radiation effects the gondola and supplies heat for the system. Albedo radiation does not exist on the dark side of the Earth, since no Solar radiation reaches it.

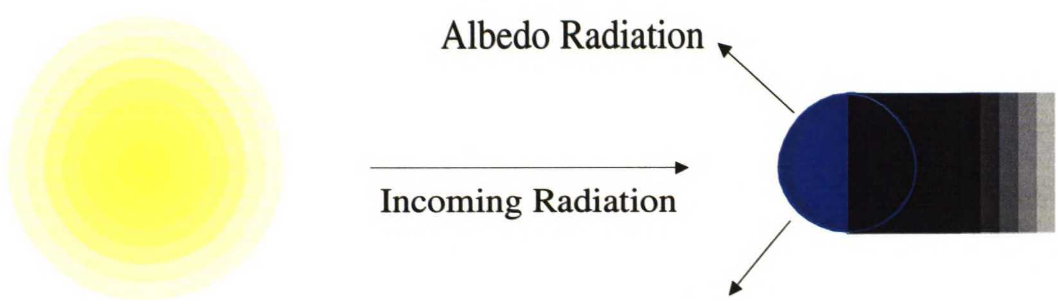


Figure 17. Albedo Radiation.

As the albedo radiation is a certain part of the incoming Solar radiation, the amount of albedo fluctuates quite much. It is dependent on different objects and materials, as the reflection properties of materials are different. The intensity of albedo radiation can be calculated through *Equation 3*.

$$I_A = I_S aF \tag{3}$$

I_S	Incoming Solar radiation
F	View factor
a	Albedo coefficient

The view factor F included in *Equation 2* describes the fraction of the total albedo radiation that actually influences the system. Value F depends on the altitude (h) of the object and of the bearing angle (ϕ) between local vertical and the direction of Sun's radiation as illustrated in *Figure 18.*

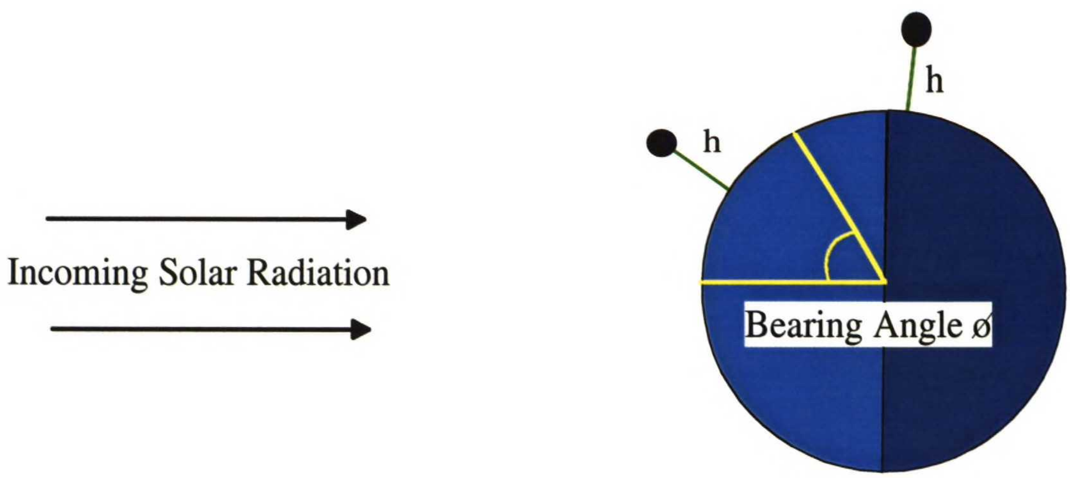


Figure 18. View Factor in Relation to Bearing Angle and Altitude.

Maximum illumination occurs when $\phi = 0°$ and diminishes as the angle increases. The relation takes into account the fact that one side of Earth is always under shadow and the other illuminated and the combined view that the object sees affects the albedo radiation it receives. As we are examining an object whose orbit is merely at 20-km altitude we can state that the albedo radiation affects the object on the dayside of Earth and vanishes as the object enters the dark side - as the bearing angle increases above 90°. This would not be the case for higher orbiting systems.

The average albedo coefficient for Earth is 0.34 but this value fluctuates quite significantly. Clouds reflect much of the incident radiation directed to them and thus have a high albedo coefficient value of around 0.8. Green land areas and cities and other urban areas tend to have albedo coefficients ranging from 0.03 to 0.3. The Moon, for example, has an average albedo coefficient of 0.07 where as Venus has its average of 0.61. [14]

5.2.2.3 Earth's Planetary Radiation

Each of the planetary bodies in the Solar system radiates heat similarly to a black body radiator. This radiation emerges from the absorbed Solar radiation and it issues from planets' atmospheres and cores and from all the objects that have stored thermal energy on the planets' surfaces. Earth's planetary radiation is mostly infra-red radiation and thus acts as a heating element. This radiation varies locally and quite extensively over periods of time, but an average long-term value is set to 237 Wm^{-2}. This radiation affects everything in Earth's vicinity and thus has an ability to provide thermal energy even on the dark side of the Earth. This differentiates the albedo and planetary radiation from each other. [14]

5.2.2.4 Heat Energy from Surrounding Air

The air surrounding the system has thermal energy, which is proportional to the temperature of the air. This temperature is again proportional to the energy output of a black body radiator and allows the determination of the radiation energy output.

As the gondola operates in low density and low-pressure surroundings, the radiation becomes the main method of heat transfer. The following thermal analysis assumes heat exchange solely by radiation and leaves out the small effect that the sparse surrounding air has on the gondola conductive-wise.

5.2.3 Night-time Conditions

During night, the one obvious difference to the daytime conditions is the lack of the Sun's radiation. In the absence of this radiation, the albedo radiation vanishes too. During night-time, the only heat sources for the balloon-gondola system are the planetary radiation, and the energy from the surrounding air. One has to remember the deep space background radiation, which is constantly affecting everything in the universe, but for our calculations its effect can be ignored, as the radiation is merely 3 K.

As the principal goal of thermal design, the different components of the system should be set to operate in a specific temperature window. In other words, the temperature should never rise too high nor drop too low. It is obvious that the maximum temperatures will be gained during daytime, when the Sun can heat the system and similarly the minimum temperatures will be present during night-time. This leads to a situation where the system should gain the same amount of heat energy during the day as it loses during the night. This would be the ideal situation; the temperature window would remain the same and the system would have the same temperatures every day during different times of the day. However this situation is almost impossible to achieve, due to variations in conditions and non-idealities of the system. If the system does not get the amount of heat energy during the day that it has lost during night-time, the system will be colder the next time it passes into the night. Again it loses heat energy and gains less the next day. This would lead to a situation of constantly declining temperature conditions, and eventually the temperatures would fall below the operating window. The same applies in reverse; too much heat energy during the day in comparison to the heat loss during the night would lead to warming and eventually overheating of the system. This is why the thermal design should focus on reaching a condition that is as close to the ideal situation as possible. Also, it is preferable to let the system gain more heat during the day than the opposite, because excess heat is much more easily taken care of. Furthermore, the conditions we are investigating suggest that we should be more concerned with keeping the system warm instead of cold.

5.3 Thermal Control of ICARUSS Platform

As the name suggests, thermal control is used to control the temperatures of a system. If we are to look at different measurement applications, most of them involve electronics and other areas of operation, which require operating in a certain temperature window. Indeed if all systems worked at any temperature, thermal control would be useless. For a given system, its planned thermal budget must be designed to give optimum temperatures for all of the different components involved. In most cases, the actual process of determining specific temperatures for all areas of the system is very difficult. Design should therefore concentrate on finding the extreme temperatures and conditions, because this will be the operational window for that system. Temperatures will settle somewhere between these values and if the system is designed so that it can operate within these extremes, the whole package will work temperature-wise.

This approach is also used in ICARUSS balloon-gondola system. The coldest conditions will be during the night and the warmest during the day. By examining the heat sources we can calculate the extreme values and start our work from there.

5.3.1 Thermal Balance

Thermal balance is achieved when the incident radiation equals the outgoing radiation. This means that the heat absorbed and produced inside the gondola must equal to the heat dissipated by the gondola. In terms of radiation two material qualities must thus be in correct proportion to one another - the absorptance and emittance of the used material. Since the Solar radiation and its components provide the gondola its heat from outside, the surface material of the gondola is the only thing that interacts with this radiation. Thus it is vital to design the surface material so that it takes in a correct amount of heat in relation to the amount it leaks out. Thus the relation between the surface material's absorptance to the material's emittance plays an important role.

Table 1. Absorptance and Emittance of Various Materials. [14]

Material	Absorptance α	Emittance ε	Ratio α/ε
Polished Aluminum	0.35	0.04	8.75
Polished Copper	0.28	0.13	2.20
Black Paint (Epoxy)	0.95	0.85	1.12
White Paint (Silicate)	0.14	0.94	0.15
FEP (2mil)/silver	0.05	0.62	0.08

Absorptance of a material is defined as the ratio of absorbed radiation to the incident radiation and emittance is the ratio of emitted radiation by a material in relation to a black body radiation in the same temperature. The definition of black body states that a black body absorbs everything radiated to it and at the same time radiates energy at the all wavelengths at maximum rate. This concept of black bodies is a theoretical concept and no such material or object exists, although stars behave quite similarly to black bodies. This definition thus states that a black body has absorptance and emittance of value 1. *Table 1* outlines few different materials and their respective absorptance and emittance values. Also included in the table is the ratio of absorptance and emittance. This is usually the property that is examined more closely as it combines the two properties and as stated has a strong influence on the thermal balance of the system. [14]

Absorptance and emittance and especially their ratio are the key features in passive thermal control methods. These and other passive methods to control the thermal balance of the gondola will be studied next together with some additional active thermal control methods.

5.3.2 Passive Thermal Control Methods

Passive control methods use passive means to control the temperature. This means that no outside power source or other factor is needed by the passive method to operate. The main passive methods are outlined next.

5.3.2.1 Materials

Materials and their properties are the first factors to be examined in thermal control method designs. By choosing the right material, a certain temperature window can be achieved if the conditions are known. In the case of ICARUSS platform the conditions will change quite significantly, but an average approximation of the temperatures both on the surface and inside the gondola can be achieved. The temperature extremes of the gondola surface must first be calculated with certain surface material absorptance and emittance values and choose the most appropriate option. This option in general terms means that, if a system requires low temperature operating point - operation in low temperatures - then it should be obvious that the selected material has high reflection and emitting capacity. This results as a low absoptance, high emittance, so that it takes in as little as possible of the radiant energy incident upon it. Similarly, an object which is designed to reach high surface temperature levels needs to be constructed of high absorptive, low emitting material. Now we can see the effect of absorptance-emittance ratio. Low values for cold-temperature-intended objects and vice versa.

As *Table 1* indicates there are several materials with their own distinguished values of absorptance and emittance. As such they can be categorized into two general groups.

- Solar reflectors
- Solar absorbers

Solar reflectors, materials that reflect most of the incident radiation, are usually white paints. Their α/ε ratio generally lies around 0.1 to 0.2. By using special techniques the value can be decreased even further. For values under 0.1 the use of mirrors or other optical reflectors is in place. These mirrors are usually located under the top surface, so second-surface mirrors is one of the names they go by.

Solar absorbers are generally surfaces with α/ε ratio bigger than one. For the balloon gondola system, the gondola should be covered with solar absorbent material. [14]

5.3.2.2 Fluid Loops

The idea behind fluid loops is connected to the high heat capacity properties of fluids. As the system enters night-time, the heat energy inside the gondola should not decrease below certain amount as mentioned before. Therefore the system must have heat restored sufficiently. By inserting a liquid container or liquid layer around the compartments, the liquid will restore a lot of heat received during the day. And as the night begins, the temperature stars to "leak" out of the compartment, it will take much longer for it cool due to the liquid container's heat energy. The liquid must be cooled at the same time as the rest of the compartment, and that takes a lot of energy. Especially, if the cooling of the liquid includes a phase shift, for example from water to ice. All this results in a warmer inside temperature of the gondola. The downside with fluid loops, which use liquids, is that the liquid itself weighs considerably. As the gondola is taken to its operating altitude by a balloon the weight-issue of the whole gondola becomes an important factor. There should be enough liquid to make the difference in temperatures, but not too much as to hinder the balloons capability to transport the gondola. On this a compromise has to be decided. [14]

5.3.2.3 Superinsulation

One feature that is important in thermal control is the insulative capacity of the material used. Good insulation ensures that a confined compartment can have a low thermal gradient around it and thus maintains a steady temperature inside the compartment. Passive insulation separates two different temperature regions from each other by preventing heat transfer between these two regions.

Superinsulation is a technique where multiple layers of insulative sheets are laid on top of each other to produce low emittance material. The gap between the layers can either be vacuumed or set at low air density to ensure low conductivity through the layers. The emittance of the total material can be radically lowered and thus superinsulation is optimal for applications requiring maximum benefit from incident radiated energy. [14]

5.3.3 Active Thermal Control Methods

Active thermal control methods use active means, such as outside power source to control the temperatures of a system. Advantage in this kind of design is the efficiency. Temperatures can be controlled to high degree and operation in hazardous environments can be maintained. The disadvantages include the need for system resources. Active components need power and they weigh considerably. As such they are not an ideal solution to the balloon-gondola system, where weight and system power are very limited. Heaters of different kind are the simplest and used active thermal control methods, since they quite simply change one energy form to heat energy. As the ICARUSS platform is designed to be single-use application no expensive parts can be implemented to it. This narrows the thermal control methods used in it to passive alternatives or simple active heaters. Power sources, such as primary batteries produce heat and this dissipated energy can be used to heat delicate compartments that require extra heat source, namely electronics compartments. Other active thermal control methods include thermostatically controlled heaters, radiation devices, thermoelectric cooling and active fluid loops. As mentioned these methods are much too heavy, power consuming and expensive to be installed into the gondola to provide heat. [14]

5.4 Quantitative Analysis of the ICARUSS Platform Thermal Design

The theoretical analysis of the ICARUSS platform operational environment focused on all the factors that influence the system. This quantitative analysis will examine the environment more precisely and differentiates different thermal control solutions from each other.

5.4.1 Platform Surface Temperatures

During daytime, the Solar, albedo and planetary radiation together with the air radiation give rise to the maximum surface temperature of the system. Each of these four sources of radiation contribute to the total power input to the system and thus heat the surface of the system to a specific temperature. The thermodynamic balance is achieved when the inputs match the output of the system. Then there will be no change in the temperature of the system. This leads to a situation where

Heat amount of the system = Heat input + Heat generated in the system - Output heat

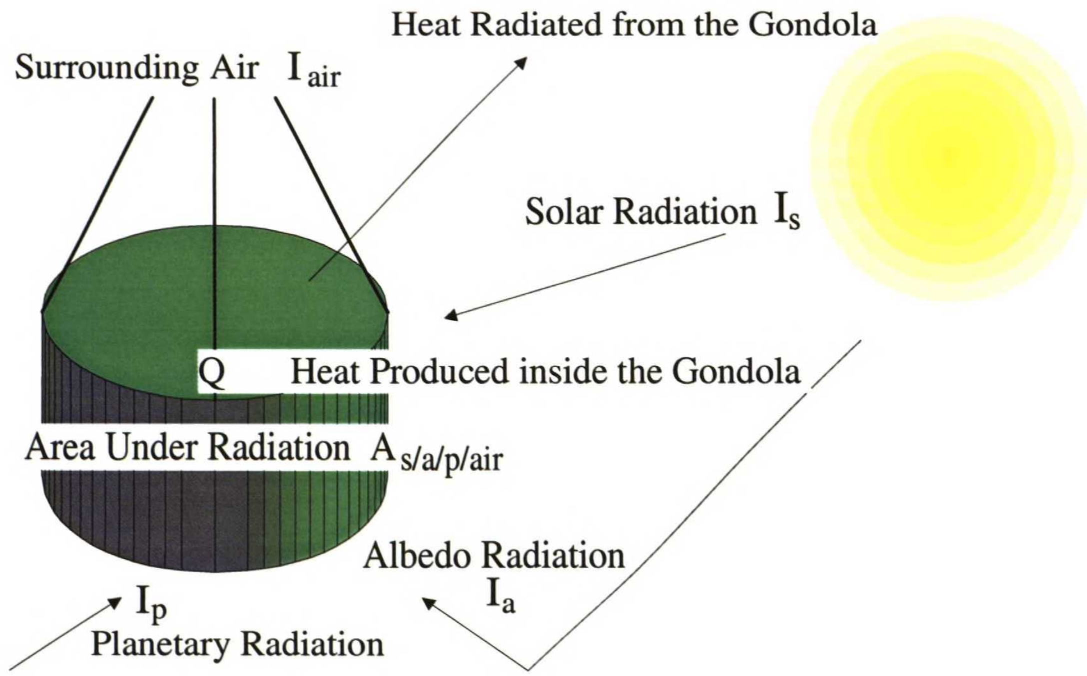


Figure 19. Heat Sources During DayTime.

Categorizing the different heat sources

- Heat amount $\qquad mc_p \dfrac{dT}{dt}$
- Input heat
  - Solar radiation $\qquad I_s \alpha A_s$
  - Albedo radiation $\qquad I_a \alpha A_a$
  - Planetary radiation $\qquad I_p \varepsilon A_p$
  - Surrounding air $\qquad \sigma T^4{}_{air} A_{air}$

- Heat generated inside the gondola Q
- Output heat (heat radiated from the gondola) $\sigma T^4_{surface} \varepsilon A_{surface}$

where

m	Mass of the system
c_p	Specific heat capacity of the system
dT/dt	Rate of change of temperature of the system
A_s	Area exposed to Solar radiation
A_a	Area exposed to albedo radiation
A_p	Area exposed to planetary radiation
$A_{air/surface}$	Gondola's total surface area (exposed to air)
I_s	Intensity of Solar radiation
I_a	Intensity of albedo radiation
I_p	Intensity of planetary radiation
α	Absorptance of the gondola surface material
ε	Emittance of the gondola surface material
σ	Stefan-Boltzmann constant
Q	Heat energy generated inside the gondola
T_{air}	Temperature of the surrounding air
$T_{surface}$	Temperature of the gondola's surface material

Combining all the factors - *Equation 4.*

$$mc_p \frac{dT}{dt} = I_s \alpha A_s + I_a \alpha A_a + I_p \varepsilon A_p + \sigma T^4_{air} A_{air} + Q - \sigma T^4_{surface} \varepsilon A_{surface} \tag{4}$$

Thermodynamic balance of the system can be achieved when there is no heat flow within the system. This sets (dT/dt) = 0 and the surface temperature of the gondola can be rearranged to

$$T_{surface} = \sqrt[4]{\frac{I_s \alpha A_s + I_a \alpha A_a + I_p \varepsilon A_p + \sigma T^4_{air} A_{air} + Q}{\sigma \varepsilon A_{surface}}} \tag{5}$$

The surface temperature of the gondola is a significant factor when designing the thermal budget for the gondola. This surface temperature sets a certain temperature gradient in relation to the inside temperatures of the gondola. If the surface temperature remains too low during the daytime, the inside compartments of the gondola do not have enough time to restore or to reach high enough temperatures, since the surface temperature falls dramatically during night-time as the heat starts to leak out from the inside. If enough heat is stored inside the gondola during daytime the heat loss during night-time will not reduce the temperatures below the desired temperature window. The gondola surface temperature equation - *Equation 5* - indicates that the temperature is mostly affected by the intensity of the input radiation and the areas that receive this radiation. Absorptance versus emittance ratio can also be noted, since the two most effective radiation sources - Solar and albedo radiation - are directly proportional to absorption and inversely proportional to emittance. This combines the surface temperature to be proportional to

$$T_{surface} \propto \sqrt[4]{\frac{\alpha}{\varepsilon}} \qquad (6)$$

This indicates the importance of choosing a right material for the surface of the gondola to obtain sufficient surface temperature to maintain adequate thermal budget. [13][14]

In the above equations, the Solar and albedo radiation equations use absorptance as the coefficient when calculating the power received by the surface. Planetary radiation, however, uses emittance. This is due to the different nature of radiation in question. The Solar and albedo radiations are short wavelength radiations whereas the planetary radiation is long wavelength infrared radiation and for this kind of radiation the emittance coefficient replaces the absoptance coefficient. This is due to the nature of materials. This assumption is valid in these studies and its main importance is to differentiate the two different kinds of radiation from each other. [14]

As indicated by *Equation 5* the maximum surface temperature of the gondola is reached when all the radiation sources are present and the minimum when the Solar and albedo radiation are not. For surface temperatures the effect of inside thermal sources will be neglected and used in the inside temperature calculations. This assumption is valid when studying the worst case scenario with no active heat sources to provide heat and also because of the fact that the heat producing compartments will be insulated quite effectively to prevent inside thermal energy to effect the outside surface temperature.

First, let us examine a spherical black body gondola with a radius of one meter. Setting the system on a one day, 12 hour day/night environment with an ambient air temperature of -70°C and varying radiation conditions, the surface temperature of the gondola - using *Equation 5* - will behave as illustrated in *Figure 20.*

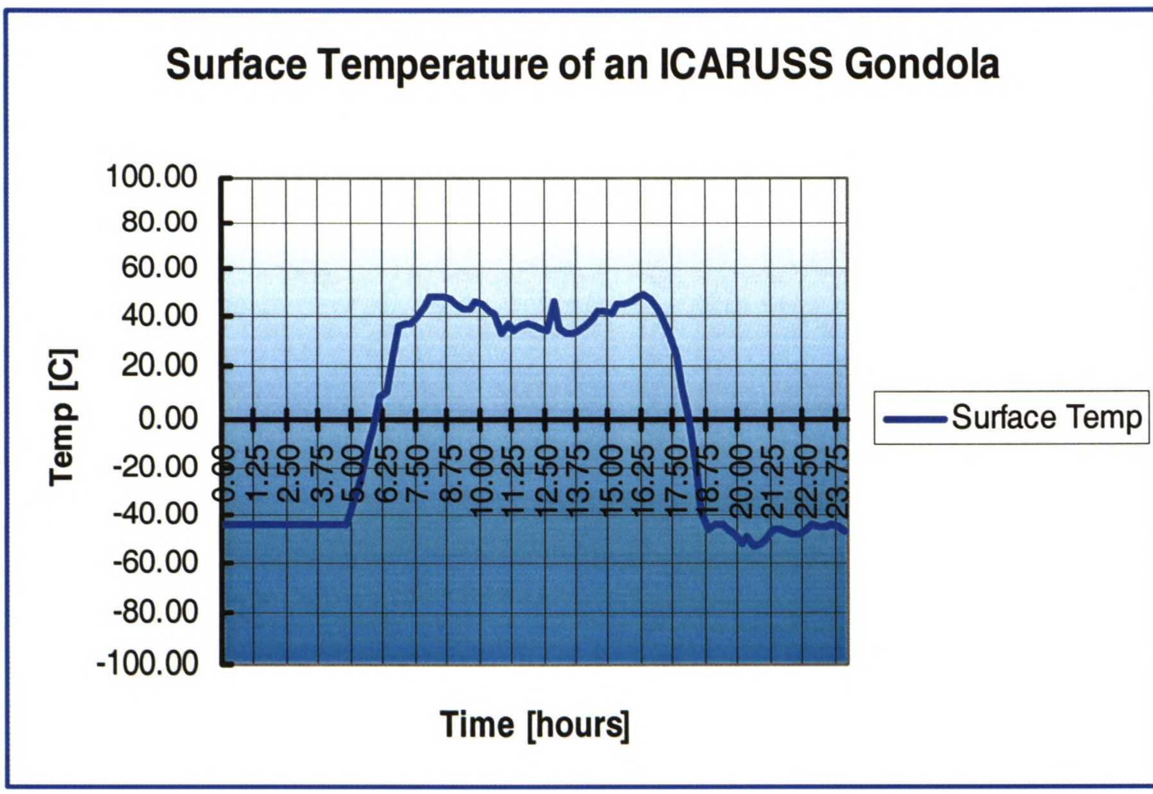


Figure 20. Computed Surface Temperatures of a Spherical Black Body Gondola.

The sunrise and sunset times can be noticed at 06:00 and 18:00. The amount of Solar radiation has been distributed over a period of one hour around the respective sunrise and sunset times to account for the gradually increasing radiation intensity illustrated in *Figure 15.* Albedo and planetary radiation have also been varied along the 24-hour cycle to illustrate the variations that can occur in these radiations - thus the rugged shape of the curve. During night-time the surface temperatures stay close to -45°C and comparing this to the ambient outside temperature of -70°C some conflict can be detected. The difference is because of the planetary radiation present during night-time hours (together with the ambient air radiation of -70°C). The used average for the planetary radiation intensity of 237 Wm^{-2} is equivalent to the energy output of a -19°C black body object, which actually sets the night-time surrounding to an average of -45°C, which appears as the average night-time surface temperature. This average planetary radiation intensity is thus subject for more detailed analysis, since through tests conducted in similar environments the gondola's surface temperature decreases rather close to ambient air temperature values - thus decreasing the impact of planetary radiation to minimum. But this theoretical analysis gives an indication of the gondola's outside temperatures and furthermore enables the theoretical analysis of the inside temperatures of the gondola, where the next generation dropsondes are housed.

Values for *Figure 20* example: $A_{air/surface}= 4\pi\ m^2$ $A_s= \pi\ m^2$ $A_a= \pi\ m^2$ $A_p= \pi\ m^2$

$I_s= 1350Wm^{-2}$ $I_a= I_s a$ $a= 0.34$ (vary) $I_p= 237\ Wm^{-2}$ (vary)

$\alpha= 1$ $\varepsilon= 1$ $Q= 0\ W$ $T_{air}= -70°C$

(Areas exposed to radiations are effective surface areas.)

5.4.2 Platform Inside Temperatures

The inside temperature of the gondola is an important factor for a reliable operation of the ICARUSS high altitude platform. Batteries, electronics and most importantly, the dropsondes are installed inside the gondola. All of them require reasonable operation temperature. The efficiency of batteries, both gondola's power source and the individual dropsonde batteries, start to deteriorate if the conditions become too cold. The same applies with the electronics. To obtain ideal operation environment for the different elements inside the gondola, the temperature should remain close to 0°C. This temperature coincides with most of the different application's ideal operation temperature and is achievable for the ICARUSS platform. As the outside surface temperatures of the gondola are now analyzed, the next step on the thermal design focuses on the interaction of this surface conditions and the conditions found inside the gondola.

5.4.2.1 Heat Exchange Inside the Gondola

The heat that is generated on the surface of the gondola will conduct through the material layers and affect the inside compartments of the gondola. These compartments, in which the equipment is stored, will have to be isolated to such a degree that the temperature does not exceed to levels that are harmful to the normal operation of the system. The influence of the heat on the surface is mainly due to conduction of heat from the surface to the inside compartments. If the insulation consists on superinsulation and thus vacuum gaps, radiation steps into play. These exchanges change the temperature of the compartments. The radiation exchange works the same way as discussed before, but the main exchange method of conduction is yet to be examined.

5.4.2.2 Conduction

Conductive heat exchange occurs when two or more materials are in contact with each other at different temperatures. Conduction itself can be characterized as energy exchange through electrons in a material. If one end of a material is heated so that there will be a difference in temperature at both ends of the material, the heat energy will flow to the cooler end through electron collisions. This rate of heat flow is proportional to the temperature difference, called the temperature gradient, and the properties of the material, as well as the area through which the flow occurs. This simple relation can be expressed as

$$\frac{dQ}{dt} = -\kappa A \frac{dT}{dx} \tag{7}$$

Q	Heat flow
κ	Thermal conductivity coefficient
A	Area of conduction
T	Temperature
x	Length

Examining the inside of the gondola, we can assume that some heat will be produced inside the compartments, mainly due to the power source of the gondola. Primary batteries produce waste energy in the form of heat. This depends on the efficiency of the battery. Low efficiency batteries produce more heat than high efficiency ones. The heat generated warms the inside of the gondola and it is imperative to take full use of this thermal energy. This heat begins to move out from the gondola by conduction as illustrated in *Figure 21.* As *Equation 7* implies the rate of heat exchange can be reduced by

- Increasing the distance between the outer surface and the inner compartments (length x)
- Decreasing the surface area of the inner compartments (area A)
- Decreasing the conductivity coefficient (coefficient κ)

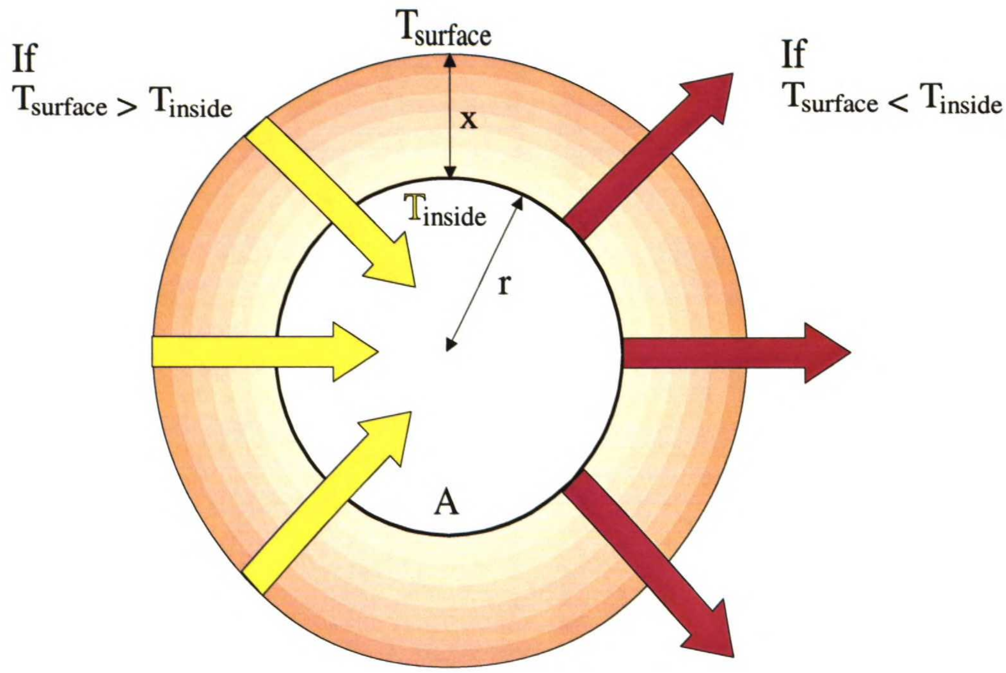


Figure 21. Heat Conduction in a Spherical Gondola.

Thus by increasing the thickness x of the insulating material, the heat produced inside the compartment can be stored more efficiently. The same applies with the reduction of the conductive area. Out of all geometrical shapes, a sphere has the least surface area compared to its volume and thus a sphere is an ideal shape to be used in insulation solutions. Also choosing low conductivity materials, such as styrofoam, the conductivity can be further reduced. This however hinders the heat from the surface to warm the gondola, when the surface temperatures are higher than the temperatures in the compartment, as the conductivity is decreased by these three factors. This implies that a compromise on the factors of the insulation has to be decided to allow sufficient insulation to prevent heat generated inside to escape but yet allow some heat from the surface to heat the inside. An important factor in this equation is the amount of heat produced inside the compartment. If none is generated, the gondola needs to have water loop installed to protect the compartments from cold. But if heat is generated inside the compartments then it is in best interests to reduce the conductivity and store that heat.

To understand the temperature changes occurring inside the compartments we must first derive the conduction environment for the gondola. Let us examine the familiar spherical gondola. From *Equation 7* we get

$$\frac{dQ}{dt} = W = -\kappa A \frac{dT}{dx} \qquad (8.1)$$

$$A_{sphere} = 4\pi x^2 \qquad (8.2)$$

$$dT = -\frac{W}{4\pi x^2 \kappa} dx \qquad (8.3)$$

$$\int_{T_1}^{T_2} dT = -\frac{W}{4\pi\kappa} \int_{x_{in}}^{x_{out}} \frac{1}{x^2} dx \qquad (8.4)$$

$$T_2 - T_1 = \frac{W}{4\pi\kappa}\left[\frac{1}{x_{out}} - \frac{1}{x_{in}}\right] \qquad (8.5)$$

$$\Delta T = \frac{W}{4\pi\kappa}\left[\frac{1}{r+x} - \frac{1}{r}\right] \qquad (9)$$

Expressing *Equation 9* in terms of work W

$$W = \frac{4\pi\kappa\Delta T}{\left[\frac{1}{r+x} - \frac{1}{r}\right]} \qquad (10)$$

the temperature gradient present between the outer surface and the inner compartments of the gondola based on the difference of temperature between the two (ΔT) can be calculated. This gradient is responsible for exchanging heat between the two areas and this exchange rises or decreases the temperature of the system by

$$Q = cm\Delta T \qquad (11)$$

where c is the specific heat coefficient, m the mass of the system and ΔT the difference of temperature. [16][17]

5.4.2.3 Temperature Response of the Platform - Electronics Compartment

By implementing the surface temperature behavior illustrated in *Figure 20* and combining the heat transfer laws described in chapter 5.4.2 we can calculate the theoretical temperature response of the system - i.e. how the inside temperatures will react to the temperatures of the surface.

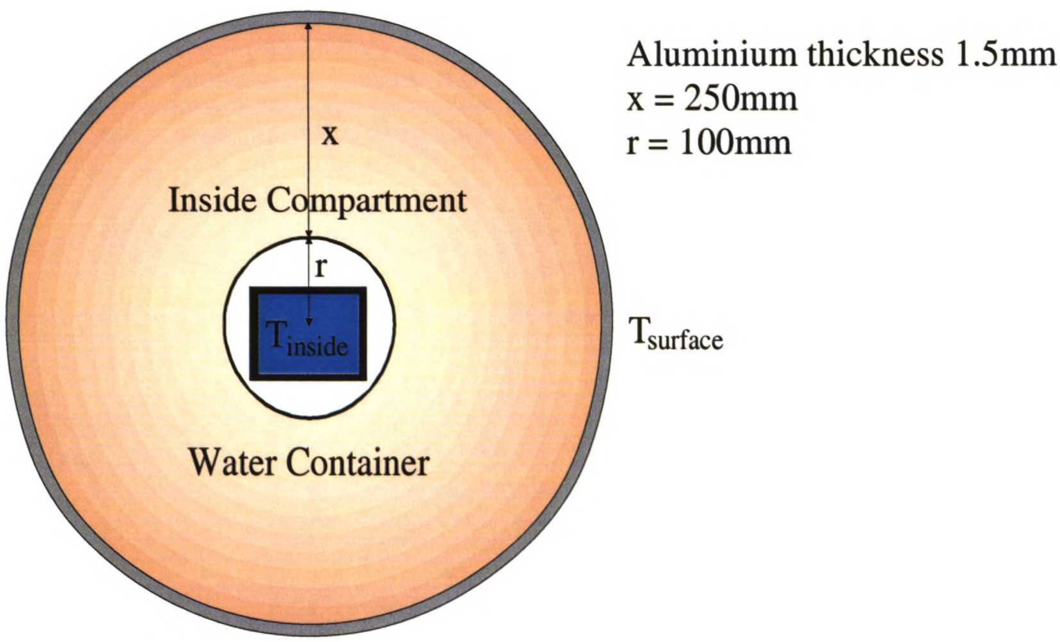
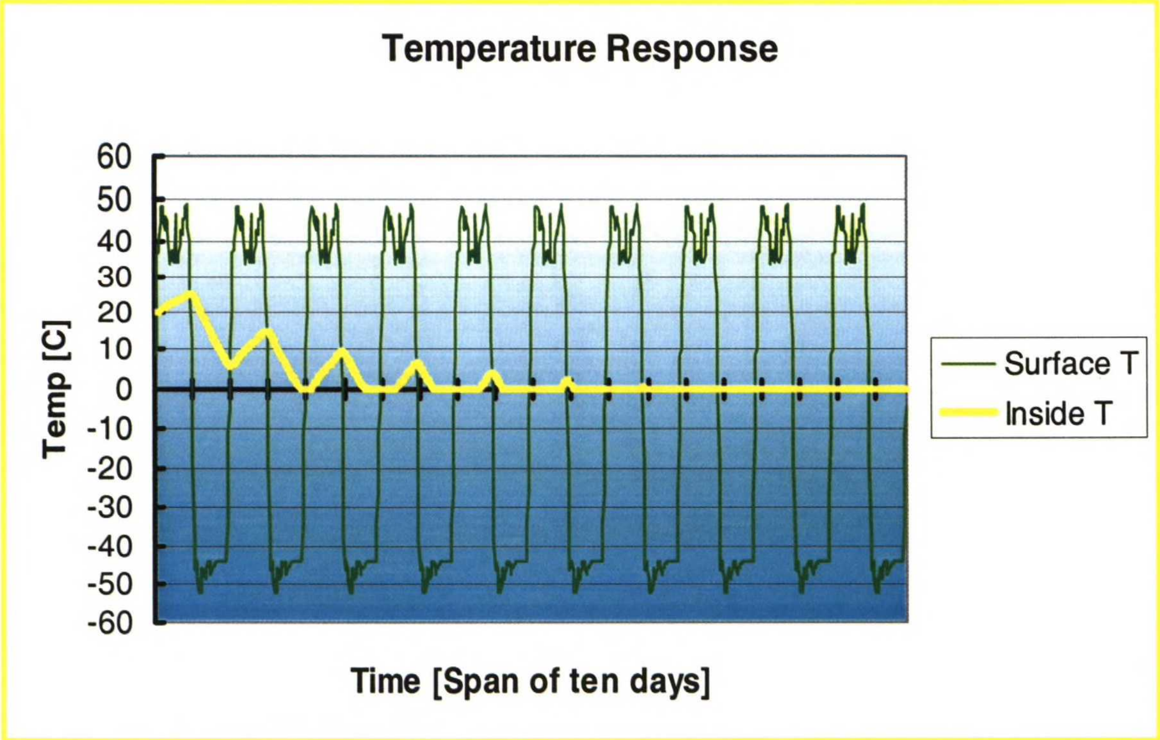


Figure 22. Inside Temperature Calculation Setting.

In the following example the gondola is spherical in shape with thin 1.5-mm aluminum layer covering the surface. 250-mm layer of styrofoam, which surrounds the simple spherical inside compartment, follows this layer. With no heat sources inside the system, the inside compartment is equipped with water container acting as a water loop insulator to store heat as the temperature gradients change over the inspected ten day period. *Figure 22* illustrates the setting.

The initial temperature of the inside container - water - is set to 20°C and the surface temperature cycle begins at 06:00 as described in *Figure 20*. The conductivity of aluminum is very high (200 J/sm°C) and the layer very thin so we assume that the outside radiation warms the entire aluminum to the calculated surface temperature. The conductivity of styrofoam is 0.033 J/sm°C and density 38.5 kgm^{-3}. The water container contains 1 kg of water and the container holding the water is assumed to perfect conductor of heat. The inside compartments temperature is thus dictated by the water container's temperature. Ideally the water container would be placed all around the inside compartment to provide all-around shield against escaping heat. *Figure 23* illustrates the temperature response of



such system in a ten-day period.

Figure 23. Computated Temperature on the Surface and Inside of a Spherical Gondola.

The daytime surface temperatures give rise to increase in the inside temperatures and vice versa. Because of the water container inside the compartment, the inside temperature does not decrease below zero. This is because of the heat energy leaking out of the compartment starts to form ice of the contained water. The heat of fusion of water is 333 kJ/kg, which simply means that 333 000 Joules of heat has to escape through the insulation in order to freeze 1 kg of water. After sixth day, the ice stays permanently in the water container and the rate of freezing - the rate of ice forming during the night versus ice melting during the day - indicates that it takes 48 cycles to freeze the entire 1 kg of water stores inside the gondola. The negative temperature response of the inside compartment can be seen from the general form of the inside temperature curve, which quite clearly decreases from the beginning. As the operational lifetime requires thermal conditions optimally close to zero degrees for 6 to 10 days, this kind of solution would prevail.

The examples given in the analysis are theoretical and ideal conditioned calculations of the environment. However they give a general example of the conditions faced by the ICARUSS platform and furthermore windows the environment quite efficiently. To study the platform from a more realistic point of view, the thermal design becomes much more complicated. The platform needs to have direct contact between the dropsondes and the outer air, in order to deploy the dropsondes. At these access points, heavy insulation cannot be used. This presents the most severe heat drain in the system. However, if active heat sources were added the inside temperatures would naturally increase. The power source, which will be installed, will definitely produce heat and this on the other hand can balance the heat drainage caused by the launch hatches to certain degree. All in all, this leaves the platform in a situation where some components can be shielded quite efficiently from the extreme cold but at the same time some components are exposed to more severe conditions. These will include the dropsondes themselves. *Figure 24* describes the possible ICARUSS gondola structure and illustrates the difference of thermal control for different parts.

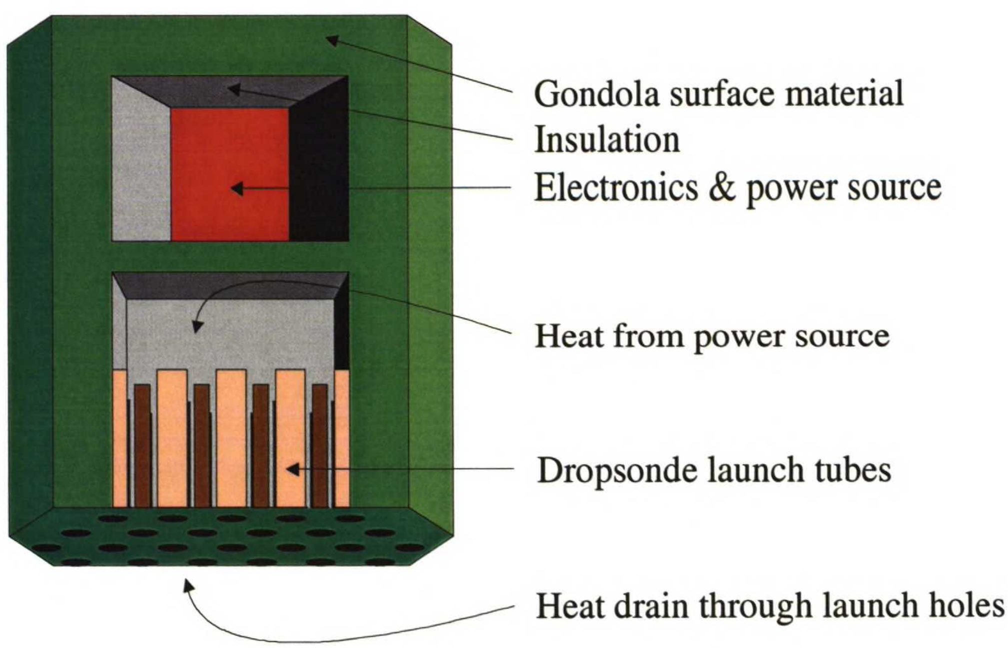


Figure 24. ICARUSS Gondola's Compartments [11].

This figure clearly illustrates two different compartments in the ICARUSS gondola - the electronics and power source compartment for which the inside temperature analysis was made and the dropsonde compartment.

5.4.2.4 Temperature Response of the Platform - Dropsonde Compartment

A general computer analysis on the temperatures inside the dropsonde compartment was also conducted. The used computer heat modelling program FlowWorks calculated the heat transfers taking place inside the predesigned ICARUSS gondola illustrated in *Figure 25.* In this analysis, the gondola's electronics compartment was generating heat at a constant rate while the outside surfaces of the gondola were kept at -70 °C. This method was used to understand the heat exchange between the two compartments and the effect of the severe heat drainage caused by the dropsonde launch holes. *Figure 25* illustrates the gondola and the dropsondes inserted in the launch tubes. The placing of the dropsondes was chosen to cover the two extreme placing inside the gondola - one directly below the heat producing compartment and the other close to the outer surface. The response of the latter was under study to learn about the worst case temperatures found in the dropsonde compartment. The result of the computer analysis is illustrated in *Figure 26* and *27.*

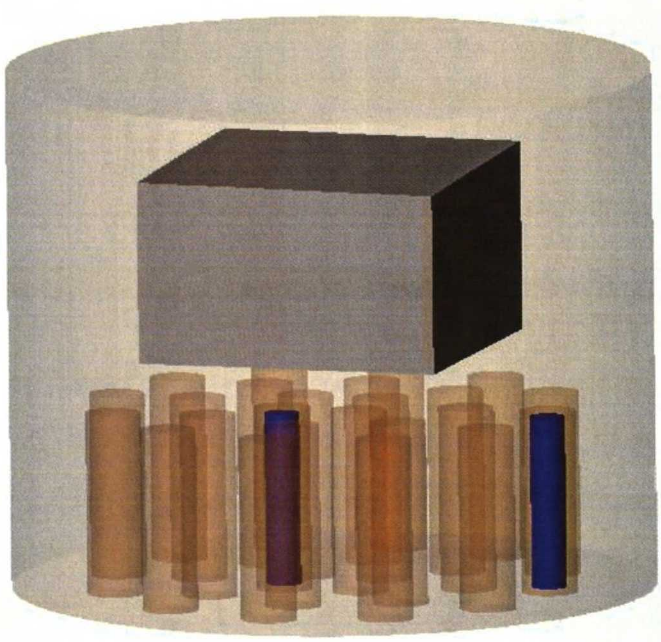


Figure 25. ICARUSS Gondola Together with Two Dropsondes.

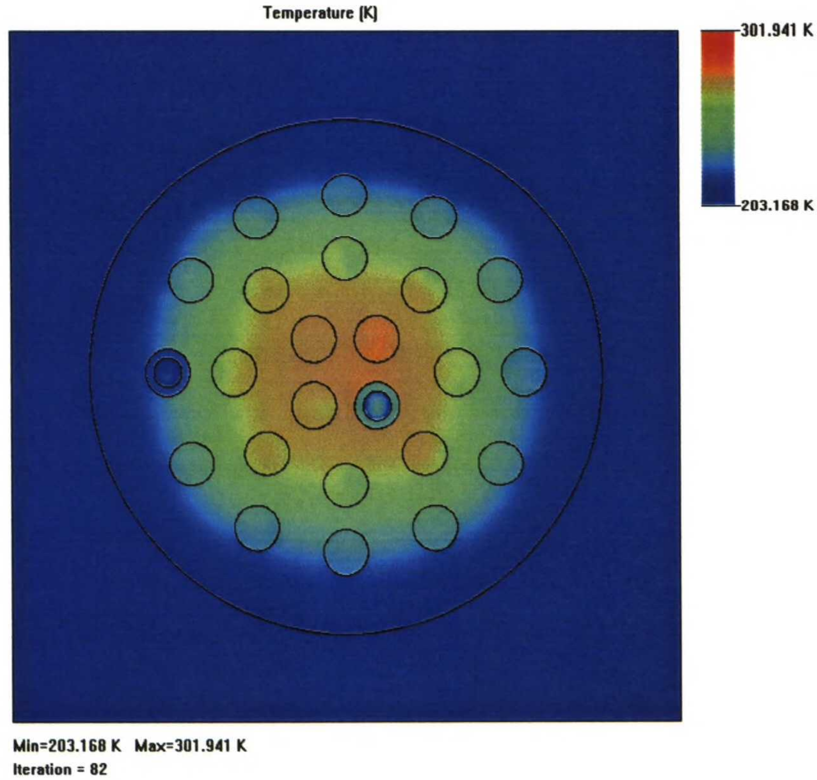


Figure 26. ICARUSS Gondola - Bottom View.

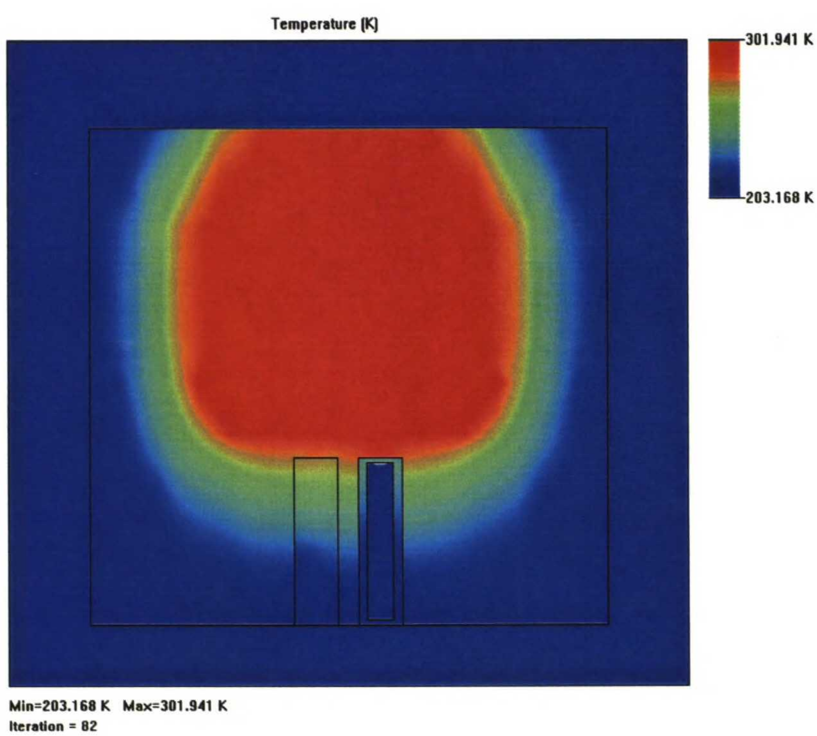


Figure 27. Side View Illustrating the Outer Dropsonde.

As seen from *Figures 26* and *27* the outermost dropsonde's temperature remains close to the ambient temperature. Even tough the electronics compartment is capable of heating the air inside a dropsonde launch tube fairly efficiently, the situation changes once a dropsonde is inserted inside - *Figure 27*.

5.4.2.5 Inside Temperature - Conclusion

This kind of general study on the temperatures found inside the dropsonde compartments must be included in the dropsonde temperature analysis and in the ICARUSS gondola's design as well. Although this example does not represent the most accurate or realistic scenario, it indicates the challenges in the thermal design of the system. As such it gives the indication that if no major temperature controlling is applied, the dropsonde indeed must survive ambient temperatures while inside the ICARUSS gondola. Thus the worst case temperature scenario for the dropsonde is set to -70 °C.

6. NEXT GENERATION DROPSONDE FOR ICARUSS

Having analyzed the ICARUSS platform and the modules of the next generation dropsonde the requirements for the dropsonde itself can be studied. The requirements arise from the specific need that the ICARUSS platform creates. This chapter describes the different specifications that are needed in the development of the next generation dropsonde and analyses the measures to be taken into account in each case. The requirements - not satisfied by the present RD93 dropsonde - and design parameters for the ICARUSS dropsonde include

- Environmental tolerance
- Automatic launch operation
- Reduced weight
- Reduced size
- Low power consumption
- Low price
- Synoptic measurement accuracy

Each of these factors has to be met by the next generation dropsonde. Specific quantaties of the weight and size or the price of the dropsonde cannot be stated at this early stage of the design, but instead only comparative requirements. Hence the weight of the dropsonde for example has to be lower than that of RD93. The analysis begins from individual modules that are required to meet these requirements mentioned above and continues to the interaction of the whole assembly of these modules, which make up the first prototype. Each of these modules is analyzed and tested according to their specific need.

6.1 Next Generation Dropsonde Modules

The modules described in Chapter 3 included all the essential dropsonde modules. The next generation dropsonde will utilize same modules, but which are designed to meet the above requirements. The following is a summary of the design specifications of these modules that has to be kept in mind while designing the next generation dropsonde.

6.1.1 GPS Module

The GPS module of the next generation dropsonde should make use of the code correlating properties of GPS wind solution. The present dropsonde RD93 utilizes the non-code correlating GPS solution and this method has been found to flaw in extreme winds, such as found from the hurricanes. Simulations made to the code correlating technique suggest that code correlating performes much better in extreme conditions.

The GPS antenna has two alternatives: the present RD93 helix GPS antenna or a patch antenna. The use of patch antenna would minimize the size of the dropsonde as the antenna element measures only centimeters in height. The helix antenna on the other hand measures close to 10 centimeters in height. This requirement for space is an important factor, since the next generation dropsonde has to be minimized in weight and size. Reliable operation however, is the factor that counts the most.

6.1.2 Transducer Unit

The main concern with the next generation dropsonde's transducer unit is the temperature difference between the transducer unit and the sensor boom. This concern has been detected in the radiosonde applications and it applies to the next generation dropsonde as well. A *radiosonde* uses a water-activated battery to provide power for the sonde. This water activated battery produces lot of waste energy in form of heat. This heat warms the inside components of the radiosonde, including the transducer unit. It has been detected that this warming of the transducer unit creates error to the sensor measurement. This is because the stray capacitance between the sensor circuit route and the sonde ground varies as a function of temperature and possibly humidity. Thus a temperature difference between the boom and the transducer unit changes this capacitance and thus changes the total capacitance of the sensor, which then shows as an error. If the modules of the next generation dropsonde and particularly the transducer unit are heated for better temperature tolerance, deliberately or by some other means, it produces error to the measurement. This situation must be avoided. Heating of the dropsonde modules should therefore exclude the heating of the transducer unit to levels that introduce noticeable error in the measurement.

6.1.2.1 Sensor Boom

The sensor boom used in the next generation dropsonde will house the temperature sensor and the two humidity sensors. The boom itself is coated with high reflecting surface to reduce the radiation error of both temperature and humidity measurement.

6.1.2.2 Temperature Sensor

The temperature sensor is constructed from two very thin metal wires that produce a capacitance between them. This construction is covered with aluminum to shield the wires from excess radiation. This thin threat measuring only 0.6 mm is vulnerable to mechanical shocks and other physical forces. The two wires forming the capacitance react to temperature change and the capacitance chances according to the following equation.

$$C = e_d \frac{A}{d} \tag{12}$$

As temperature changes, the dielectric between the capacitor wires reacts accordingly - change of permittivity of the dielectric $\mathbf{e_d}$ in *Equation 12.* This change in capacitance then changes the frequency of the circuit, which is then modulated to the transmission message.

6.1.2.3 Humidity Sensor

The humidity sensors are constructed with thin film technology. This technology allows the humidity sensors to be produced out of extremely thin conducting plates that work as a capacitor. The capacitor dielectric - substance between the capacitor plates - is then selected to be affected by the relative humidity of the surrounding air and thus enable the humidity measurement. This can be seen as the change of $\mathbf{e_d}$ in *Equation 12.* This construction is again mechanically very small and easily effected by mechanical stress.

As the upper electrode of the sensor has to be porous to allow water vapor to penetrate it and affect the capacitor dielectric, the humidity sensor is subject to contamination. This contamination fills the porous holes located in the upper electrode and thus affects the amount of water vapor reaching the dielectric. Therefore contamination usually results in a reduced humidity reading as less water vapor is allowed to the dielectric. Contaminated sensors can be purified by regenerating them. The process of regeneration requires that the dielectric is heated to a temperature of 180°C for 5 minutes. This heating is usually done with a heating resistor embedded in the dielectric by applying appropriate voltage. This voltage and thus the heating elements resistance has been set to 24 Volts in the humidity sensor configuration, which will be used in the next generation dropsonde. This regeneration of the humidity sensors must be conducted prior the launch of the dropsonde to ensure humidity measurement with accurate and pure sensors.

Contamination shields are the alternative method of keeping the sensitive humidity sensors clean. These shields are simple plastic containers that can be placed around the sensor boom. Usually an active absorber, which absorbs contaminants, is placed inside the container. The removal of the shield could become difficult in an ICARUSS platform, where all launch preparations must be automatic.

6.1.2.4 Pressure Sensor

The next generation dropsonde pressure sensors are silicone-based microsensors. The difference in pressure causes two conductive plates to contract or expand and this can be detected as a change in capacitance. The distance **d** changes in *Equation 12* and thus changes the capacitance.

6.1.3 Plug Ins

As the ICARUSS platform has to be fully automatic and as the dropsonde has to be linked to the platform prior to the launch, the connection that connects these two has to be kept as simple and as robust as possible. The basic task of this link is to make sure the dropsonde is ready to be launched on time and apply additional data or power if needed. For example the regeneration of the humidity sensors could be conducted through this link and use the platform's power source to apply necessary power for the task. By using galvanic connection - copper wires with a connector attached to the dropsonde body - the link would prove reliable, but the fact that the dropsonde must be detached from the plug before or at deployment creates another requirement.

6.1.4 Power Source

The power source represents the densest module of the next generation dropsonde. Given the requirement of minimal weight and size of the dropsonde, the power source used has to be carefully designed.

The requirement of reliable operation in cold temperatures narrows the possibility of the power source to lithium based batteries. Other commercial power source types simply do not meet the requirements. As the weight and density of the batteries is an important factor, the number of batteries used inside the dropsonde has to be minimized as well. Generally this means low output voltage.

Because the battery provides power for all the modules of the dropsonde, all the modules must meet the low output voltage restriction set by the battery. However, voltage choppers can be used to chop the battery voltage to higher voltage levels and thus provide higher voltage levels if needed. The use of voltage choppers again needs to operate reliably in extreme conditions and as such set high demands for it.

6.1.5 Transmitter

The transmitter used in the next generation dropsonde must send the measurement data back to the gondola - see *Figure 11*. Thus the transmission module must be designed to be capable of transmitting data over the maximum distance between the gondola and the dropsonde. Thus the analysis of the distances involved becomes important.

Graphical analysis of the transmission distance analysis is included in the Appendix **[A4 Average]** **[A5 Severe]** and **[A6 Absurd]**. These three different cases - from average wind conditions and average descent rates to strong upper-air winds that move the gondola away from the dropsonde as it descents - cover the distance analysis quite efficiently. Each of the analysis place the dropsonde to an initial altitude of 25 km. By using the descent analysis described in Chapter 6.1.6 the descent rate can be calculated to get the vertical motion for the dropsonde. Adding different wind conditions, the horizontal component of the drop can be added to the analysis. The averaged winds have been calculated from series of coastal sounding stations' radiosonde wind data and then used in the Average-analysis. The two more extreme settings have horizontal winds higher than this average and thus increase the distance between the gondola and the dropsonde.

According to this analysis the transmission module should be able to send data over distances of 90 km. This requirement has to be included in the next generation dropsonde's transmission module specifications. Even worst cases - longer distances - should also be considered.

6.1.6 Parachute

Presently, the parachute is used to slow the rate of descent to a level, which enables sufficient data resolution. In general this means, that certain number of measurements can be made within a certain distance traveled. Thus the rate of descent is directly linked to the data resolution of the dropsonde.

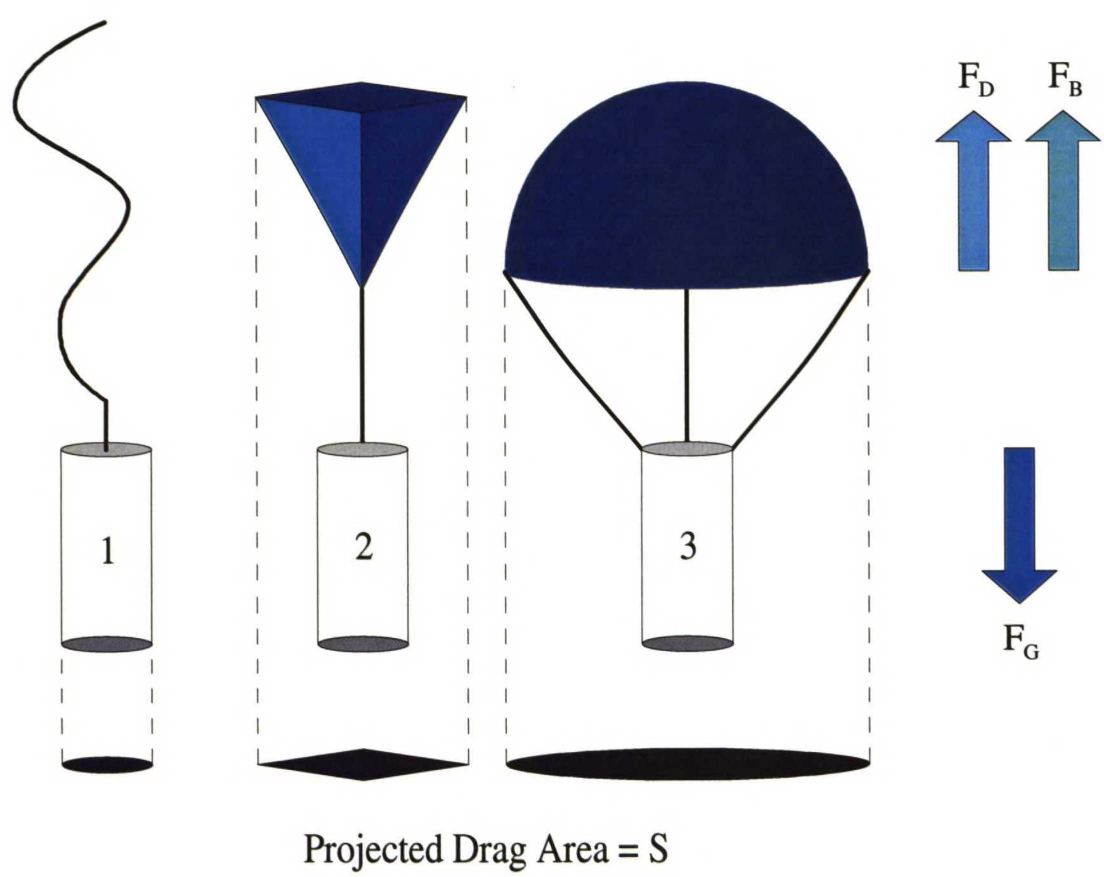


Figure 28. Dropsonde Descend Alternatives.

This setting allows the dropsonde to be used within two operational extremes - slow rate of descent - large parachute *Figure 28 (3)* - and slow data resolution versus high descent rate - no parachute at all *Figure 28 (1)* - and fast data resolution. Both extremes ideally leading to the same end result - certain amount of data samples from certain distance traveled. Because the wind direction and strength are calculated from the horizontal movement of the dropsonde, the parachute must not provide extra movement in that direction. Ideally a dropsonde should drop not glide. Any parachute used in a dropsonde introduces an error to this measurement and it is necessary to minimize this error. This also includes the concept of equipping a dropsonde with a simple streamer, which only keeps the dropsonde in an upright position while allowing clear vertical descent, and allowing the dropsonde to descent at its maximum terminal velocity.

The descend analysis is illustrated in *Figure 28.* The analysis takes into account the variations in the terminal velocity experienced by a dropsonde equipped with different parachutes or streamers. The analysis does not take into account the gliding characteristics of a certain parachute, but merely focuses on the vertical rate of descent.

Terminal velocity is achieved when the forces acting on the dropsonde are equal - $F_G = F_D + F_B$.

F_G	Force of gravity
F_D	Drag force due to air
F_B	Buoyant force - negligible in air

This relation simplifies into following equation of terminal velocity

$$F_G = F_D + F_B \qquad (13.1)$$

$$m_o g = \frac{1}{2}\rho_a C_D S v_T^2 + \rho_a g V_o \qquad (13.2)$$

$$v_T = \sqrt{\frac{2g(m_o - \rho_a V_o)}{\rho_a C_D S}} \qquad (13.3)$$

Equation 13.3 includes all the factors affecting the vertical movement of a free falling object. The effect of buoyant force in air is quite negligible as the buoyancy creates a lift proportional to the weight of the displaced air by the dropsonde. The variable most affecting the terminal velocity is the relation between the mass of the object to the drag coefficient multiplied by the projected surface area.

$$v_T \propto \sqrt{\frac{m_o}{C_D S}} \qquad (14)$$

From *Equation 13.3* the drag coefficient C_D of different dropsonde packages is the only unknown and thus needs to be tested. The drag coefficient of different parachutes or dropsonde surfaces depends on the material of the falling object. Most clearly this can be illustrated by the fact that very dense parachute fabrics, that do not allow any air to pass through, create more drag than those that are porous do. [16]

6.1.7 Mechanics

The dropsonde mechanics consist mainly on the outer structure of the dropsonde and the interior module placing. As stated, the concept of packing the different modules of the dropsonde module-wise is the starting point of the mechanical design. Different modules need to be packed as efficiently and with as little waste space as possible. The outer structure can then be applied all around the interior modules. The shape of the outer structure should be tubular to avoid any unwanted disturbances during descent due to sharp corners or angles in the dropsonde body.

Thermal insulation needs to be used inside the next generation dropsonde. The need for this insulation arises from the requirements that all the modules and components must operate in cold conditions. Given the possibility that all of the modules or their components do not meet this requirement, active heating elements must also be placed to provide heat to these elements. Again circular shape of the dropsonde structure would provide centered and optimal insulation capability for the dropsonde interior components.

On the location of the modules few requirements exist - the GPS antenna and hence the GPS module must point upward, the sensor boom and thus the transducer unit must point downward to measure undisturbed air and the parachute attachment must be placed at the top of the dropsonde. Other modules must be packed according to these specifications.

6.2 Temperature Tolerance

Temperature tolerance of the entire ICARUSS system is the most important factor that has to be accounted for. All the modules and components that make up the modules must operate sufficiently in this extreme cold condition. Even the simplest component can become obsolete in extreme cold conditions and compromise the operation of the dropsonde. As suggested in Chapter 5, the temperatures in the dropsonde compartment can be close to the ambient temperatures of -70°C. This temperature level sets the most demanding operational requirement for all the modules and components, since traditional parts - electronics or mechanical parts - usually fail to operate in these conditions. Since the last dropsonde to be deployed from the ICARUSS platform has to spend up to a week in the launch compartment with changing temperature conditions ranging from extreme cold to warm conditions, the requirement for it to remain accurate and reliable through the whole time period is quite demanding. Thus the testing of the modules will mainly focus on the temperature tolerance. Warming of the modules is also an alternative solution to solve the problems of low temperature operation. This however can have unwanted side effects.

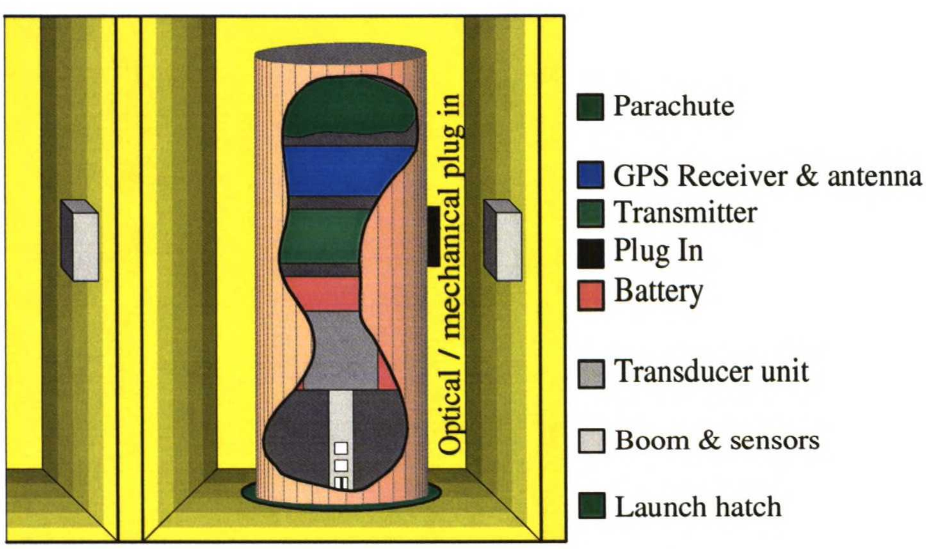


Figure 29. Dropsonde Modules in an ICARUSS Launch Compartment.

The following chapters individually address each module's specific need to meet the requirements set by the ICARUSS platform environment. *Figure 29* illustrates a dropsonde and its modules in the ICARUSS platform.

6.2.1 Effects of Temperature Extremes on Sensors

The measurement sensors form one of the most important concepts of the entire dropsonde system. The purpose of a dropsonde is to gather accurate and reliable measurement data from the atmosphere and this requirement is not and will not be disregarded or diminished in any application they are used in. One of the major elements in the study of low temperature's effect on the sensors is how the sensors will react if they are exposed to low temperatures for a long time and then turned on. This cold starting of the sensors affects all the sensors. Also the ice accumulating on top of the sensors can cause errors in the sensors operation. This affects especially the humidity sensor since any substance touching the sensor surface has direct effect to the sensor reading.

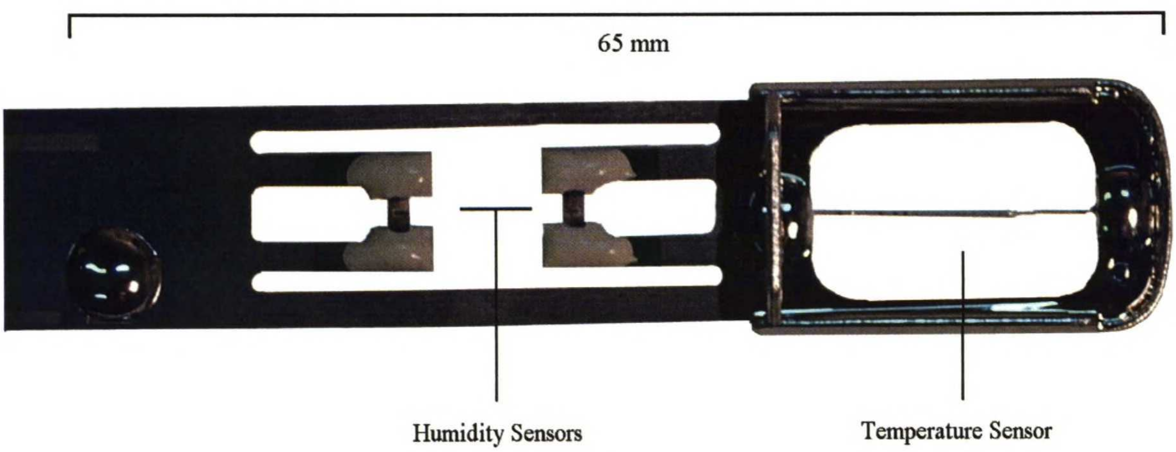


Figure 30. Sensor Boom.

6.2.1.1 Temperature Sensor

Cold temperatures should not however have significant effect on the temperature sensor's behavior or to the reliability of the sensor. Cold starting the temperature sensor will be studied in detail.

6.2.1.2 Humidity Sensor

The presence of changing temperature conditions and low pressure levels should make the environment free of contaminants but as the ICARUSS platform is launched from ground it must ascend to its operating altitude and be subject to contaminants on the way - i.e. smog clouds from nearby cities. This possible contamination must then be purified by regeneration and performing regeneration in extreme cold and low-pressure conditions can have unwanted side effects. One of them being the over heating of the dielectric, which melts the dielectric substance when heated above 200°C. This over heating could be caused due to the low pressure environment's impact on the heating element. There is very little air surrounding the sensor to cool off the heat caused by the heating element. Thus regeneration of the humidity sensors in cold and low-pressure conditions is an important issue to be studied.

As mentioned earlier, the possible accumulation of ice on top of the electrode will effect the sensor reading. The heating resistance can be used to melt the ice and solve the problem of freezing for humidity sensor.

6.2.1.3 Pressure Sensor

The operation of the pressure sensor in cold conditions must tested and analyzed and particularly the impact of cold starting the sensor. Other symptoms caused by low temperature and pressure conditions will also be studied.

6.2.2 Temperature Tolerance of Transmission Circuitry

The transmitter module will be exposed to low temperature conditions as well. This will possibly affect the transmission crystal and its behavior. The possible frequency drift of the crystal frequency must be taken into account. The possibility of having to rely on the heating of the crystal or another component that fails to meet the requirements set by cold temperatures must be kept in mind.

6.2.3 Effects on Power Source

Most conventional power sources do not operate in cold conditions. -5°C is a proper temperature limit for standard alkaline batteries. Even standard lithium batteries - which can operate in colder conditions than alkaline batteries - do not operate below -20°C. Yet the power source used in the next generation dropsonde must survive long duration in temperatures as low as -70°C.

Cold temperatures affect the voltage output of a battery. A standard battery is constructed of three elements - anode, cathode and the electrolyte between these two. On water based electrolytes, one centigrade temperature increase of the electrolyte increases the chemical reaction between the anode and cathode by 2%. If the electrolyte is allowed to freeze, the reaction is stopped. On water based electrolytes this occurs around -20°C depending on the electrolyte composition. Thus by decreasing the operation temperature of a water based battery by -20°C the output voltage is reduced by a factor of 48.6%. Lithium-anode batteries do not have water based electrolytes because of the hydroscopic nature of lithium and are therefore the main candidate for the next generation dropsonde power source. Their performance is reduced similarly by decrease in temperature but they can operate in more extreme conditions.

The operation of the battery is crucial. The dropsonde battery must be able to produce sufficient amount of power from the time the dropsonde is prepared to be deployed. Given that the temperature around the dropsonde at that time is close to the ambient temperature - which accounts for the worst case scenario - the possibility of heating the battery must be accounted for. This heating system would then have to rely on outside power source, namely the gondola's battery, if the dropsonde's own battery could not deliver sufficient power for the heating. The amount of heating necessary and the heating time are factors that will be examined in more detail. [18]

Voltage choppers consist of descreet components and of these the capacitors are most effected by temperature extremes. Especially aluminum capacitors must be avoided and the use of ceramic capacitors is recommended.

6.2.4 Effects on Electronics

Electronic components, such as MOS circuits behave differently under different temperature conditions. The behavior can have more implicit effects on different parts of the dropsonde system, such as the operation of the sensors. The possible malfunction of some of the components in any of the modules must be accounted for. Again the possibility of heating the electronics must be considered as an option. [19]

6.2.5 Effects on Platform Communication

Given the possibility of freezing, the detachment of the connection could become compromised. Optical link on the other hand would not have to worry about the detachment but more so with the reliability of the data link and the lack of outside power. Dirt or ice forming on the surface of the optical sensors can cause deterioration of the link.

6.2.6 Parachute Operation

The operation of the dropsonde's parachute is vital. The long storage time in changing temperature conditions can cause condensed water on the parachute surface to freeze and possibly to prevent the parachute from deploying by the ram air. Careful packing of the parachute in dry conditions to avoid trapping of water vapor inside the parachute and dry launch tube conditions for the dropsonde should prevent the freezing of the parachute.

6.3 Pressure Tolerance

Low ambient pressure effects the next generation dropsonde's performance. As indicated in Chapter 5.2.1, the ambient pressure around the ICARUSS gondola is 100 to 50 hPa. This pressure also exists inside the gondola and the next generation dropsonde. Thus all the modules and their components are exposed to this pressure environment.

Primarily low pressure affects the rate of heat exchange by reducing conduction and convection. This can lead to an increased heating of individual electrical components, since the cooling effect of dense air is reduced.

The effect of reduced ambient pressure is not as significant as the low temperatures present in the ICARUSS environment, but this low pressure environment has to be included in all the major tests done to verify the operation of the next generation dropsonde.

6.4 Automatic Launch Operation

The ICARUSS platform requires that the dropsonde is fully functional at the time of the launch. This includes that the dropsonde has been checked for all essential operations, such as communication with the platform, all the sensors measure and deliver data, regeneration of the humidity sensor accomplished etc. In a case a dropsonde fails to comply with these requirements the platform must be able to reject the dropsonde and concentrate on the next one. The environment the platform resides in also affects this automation and thus all the factors included in the automation must be sufficiently designed to survive in these environmental conditions.

6.5 Weight and Size of the Dropsonde

The designed lift capacity of an ICARUSS balloon is 40 kg. As designed, the platform is to take 24 dropsondes with it along with the platform construction, power source and transmission/receiver systems. This implies that the weight of the platform must be carefully planned. The RD93 dropsonde weighs 0.425 kg making it too heavy for an individual dropsonde's weight. 24 dropsondes with individual weight of 0.425 kg would take 1/4 of the total lift off capacity of the ICARUSS platform. Thus weight has to be minimized and kept as a design specification in the design process. Also the size of the dropsonde must be minimized to reduce the weight of the dropsonde itself and also to reduce the weight of the gondola housing the dropsondes. This demands that all of the modules are to be kept as small as possible and to fill the interior as compactly as possible. Waste space due to oversized modules must be avoided.

6.6 Power Consumption of the Dropsonde

The battery installed to each next generation dropsonde must come in terms with all the mentioned design issues. The size and weight of the dropsonde cannot exceed certain levels and thus the battery used in the dropsonde cannot have large dimensions or large mass. For it to operate certain type of insulation and preheating elements might be needed and they require space. This implies that the power source should not have excess capacity stored in it with the expense of space. This again requires low power consumption. Presently the RD93 uses 2.9 W of power (0.16A * 18 V) during normal operation. This number has to be reduced significantly with low voltage batteries operating in the voltage range of 5 V.

6.7 Cost Structure of the Next Generation Dropsonde

One of the goals of the international projects was to obtain data cost efficiently from data sparse areas. This can only succeed, if the price of one dropsonde can be kept low.

Expensive solutions would clearly solve many of the design dilemmas, but the expenditure on the different modules cannot become too expensive. In the design phase the modules and their components must at all times be subject to price evaluation.

6.8 Synoptic Measurement Accuracy

As the next generation ICARUSS platform dropsonde will make the synoptic sounding grids more efficient by making measurements in data sparse areas, they must perform as accurately and reliably as the radiosondes used in ground stations.

Table 2. WMO Accuracy Requirements for Synoptic Measurement. [20]

Measurement	Range	Accuracy Requirement
Pressure	From surface to 5 hPa	± 1 hPa
Temperature	From surface to 100 hPa	± 0.5 °C
	From 100 to 5 hPa	± 1 °C
Relative Humidity	Troposphere	± 5 RH
Wind Direction	From surface to 100 hPa	± 5 ° for less than 15m/s
		± 2.5 ° at higher speeds
	From 100 to 5 hPa	± 5 °
Wind Speed	From surface to 100 hPa	± 1 m/s
	From 100 to 5 hPa	± 2 m/s

WMO - World Meteorological Organization - oversees these requirements and sets the standards for the data precision. If the next generation dropsonde is to provide denser sounding grid, it naturally has to meet these requirements. The accuracy requirements for upper air measurement for synoptic use are given in *Table 2.* [20]

6.8.1 Temperature Sensor Accuracy

The dilemma of measuring temperature of a substance - such as air - is that each measuring device measures its own temperature and not the substance's. The device's temperature is affected by three heat transfer factors - conduction, convection and radiation.

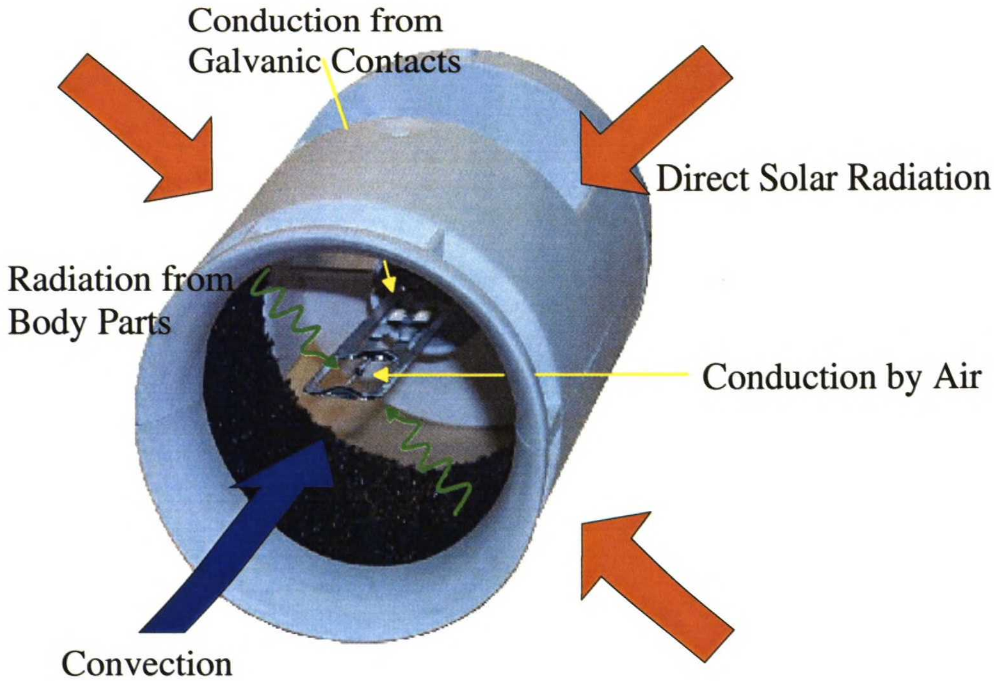


Figure 31. Sensor Boom Thermal Environment.

The temperature detected by the temperature sensor can be expressed as follows

$$Q_{conduction} = -\kappa A_s \frac{dT}{dt} \quad (15.1)$$

$$Q_{convection} = -hA_s(T_s - T_a) \quad (15.2)$$

$$Q_{radiation} = I_{sun}\alpha(A_{sun} + A_{albedo}aF) + I_p \varepsilon A_p - \sigma T_s \varepsilon A_s \quad (15.3)$$

Combining into single equation - *Equation 16*

$$m_s c_s \frac{dT}{dt} = I_{sun}\alpha(A_{sun} + A_{albedo}aF) + I_p \varepsilon A_p + \kappa A_s \frac{dT}{dt} - hA_s(T_s - T_a) - \sigma T_s \varepsilon A_s$$

we notice the dependency of each heat source. As stated by *Equation 16* the only factor that is directly effected by the temperature of the air - T_a - is the convective heat transfer. Conduction and radiation bring extra heat to the sensor and thus differentiate the temperature of the sensor from the temperature of the air. Ideally a sensor should therefore be affected by convection only. [17]

Conduction transfers heat from the dropsonde body parts to the sensor - mainly from the contact point of the sensor boom and transducer unit. Convection - the mass movement of air molecules over long distances - takes place, as the sonde is moving. This heat transfer constantly brings undisturbed air in contact with the measurement device and the structures around the sensor, which in turn change their own temperature by conduction. Radiation provides thermal energy to both air and the measuring device. The amount of received energy depends on the material characteristics. Absorbtance and emittance of infra-red radiation from Sun and surrounding air set the amounts of absorbed energy and emitted energy by the object. If the absorbed and emitted infrared radiations of the measuring device are the same, radiation does not produce extra thermal energy to the device. On the other hand, if the values differ, the material either cools or warms, in relation to the ambient air. This results as an error in the measurement. This radiation error increases with altitude since the air becomes less dense and convection and conduction start to decrease.

A *radiosonde* sensor boom is analyzed against these errors. Furthermore, the placing of the boom is designed so that the sensors are as far away from heat producing elements of the *radiosonde* as possible. Thus no extra radiated energy from the *radiosonde* parts can influence the sensors. As the dropsondes use identical sensor booms, the placing of the boom becomes an issue.

Placing of the sensor boom in a dropsonde differs from the radiosonde sensor boom placing. The importance in the placing is to locate the boom so that it detects undisturbed air. In *radiosonde* applications this means that the sensor boom has to point upward. In a dropsonde application the placing is reversed. This is due to the direction of propagation - *radiosonde* ascending, dropsonde descending. At present, the RD93 dropsonde has a plastic collar around the sensor boom to provide extra support for the boom and to make it possible for the dropsonde to stand in an upright position without bending the sensor boom - See *Figure 31*. However, this protective collar introduces a radiation source, which is located very close to the sensors. This undoubtedly effects the sensor readings. Studying the performance limits of a synoptical measuring devices issued by WMO, the recommended accuracies are as *Table 3* indicates.

Table 3. Recommended Synoptical Temperature Accuracies for Measurement Devices. [20]

Region	Pressure Level	Synoptic Accuracy
Extratropical troposphere		0.15 °C
Equatorial troposphere	Lower troposphere	0.15 °C
	Upper troposphere	0.15 °C
Extratropical troposphere	200 hPa	0.3 °C
	100 hPa	0.3 °C
	50 hPa	0.3 °C
	10 hPa	0.3 °C
	5 hPa	0.3 °C
Equatorial stratosphere	100 hPa	0.3 °C
	50 hPa	0.3 °C
	10 hPa	0.3 °C

At ICARUSS platform pressure levels of 100 to 50 hPa, the error in the temperature measurement should not exceed 0.3 °C. Studies catalogued in the WMO publications suggest that temperature sensors which are mounted close to a black surface protective materials, such as the collar used in RD93, can produce up to -0.3...0.2 °C radiation error at 100 hPa levels. [20] All Vaisala sensors are given an uncertainty value, which includes calculated probability of error in a sounding. This uncertainty value takes into account all the error producing elements present during a sounding - including radiation error. Given the uncertainty of the temperature sensor - to be used in the next generation dropsonde - in soundings of 0.5 °C, the cumulative inaccuracy together with the error caused by RD93 collar exceeds the accuracy requirement set by WMO - see *Table 2*. Worst case scenario for the temperature sensor error would add up to 0.7 °C. The use of Vaisala core sensors is mandatory in the next generation dropsonde application and as such the uncertainties that exist cannot be discriminated in different applications. The applications to which the sensors are placed introduce the additional error sources - such as the RD93 protective collar. Thus it is advisable that the sensor boom has to be placed away from the body parts of the next generation dropsonde to ensure adequate accuracy for synoptic measurements. [20]

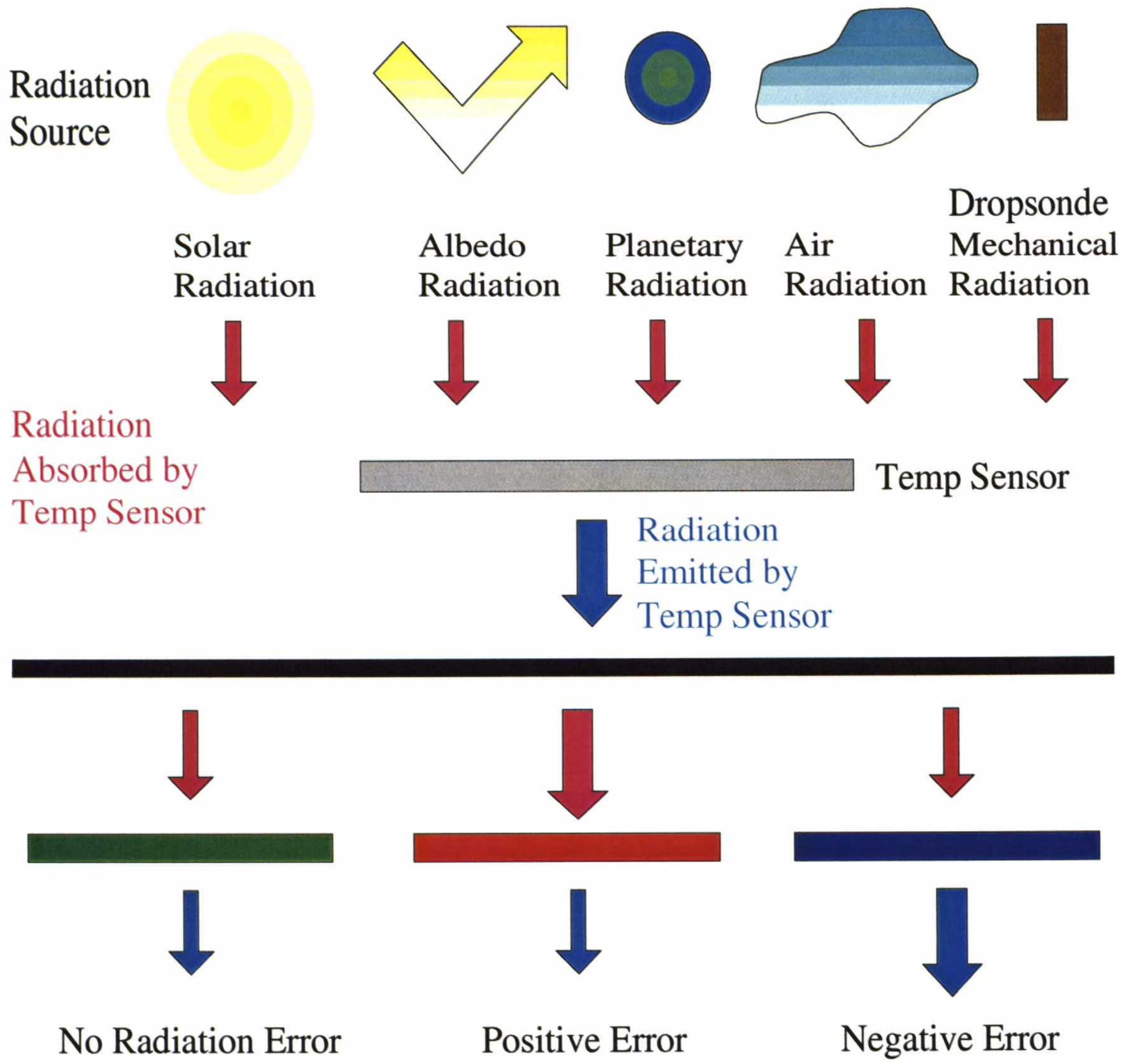


Figure 32. Radiation Error in Temperature Sensor.

Placing of the temperature sensor in relation to the position of the Sun should be designed so that the sensor has minimal surface area against the Sun. *Figure 32* illustrates this setting and accounts that the temperature sensor must see as few radiation sources as possible to achieve radiation error free measurement. The temperature sensor will produce no radiation error if the amount of absorbed radiation equals emitted radiation. However, if the absorbed radiation exceeds emitted radiation, the sensor will warm and give out too warm measurement in form of positive error. Negative error is produced the opposite way. This setting demands that the mechanical structure of the next generation dropsonde provides protection from direct Solar radiation, but at the same time reduces the radiation error from the protection to minimum. Considering the possible temperature measurement errors in a dropsonde application, three factors can be summed up

• Dropsonde application protective collar causes additional radiation error

• Collar shields the temperature sensor from direct Solar radiation - thus decreasing radiation error

• Convection is greater in a dropsonde than in radiosonde application, which reduces the effect of radiation error

The rationale for the third factor rises from the fact that a dropsonde descends at a rate of +40 m/s at altitudes of +20 km, whereas a normal radiosonde ascends at a constant rate of ~6 m/s.

The effect of each three factors must be studied and more importantly tested to learn which error source becomes dominant.

6.8.2 Humidity Sensor Accuracy

Vaisala humidity sensor operation is described in 6.1.2.3. As stated, the sensor reacts to the relative humidity of the medium it resides in. The polymer has temperature dependence as well. This dependence causes the polymer to react to differences in temperature. This temperature dependence is removed from the humidity sensor measurement by using temperature measured by the temperature sensor. Ideally, if both temperature and humidity sensors are at the same temperature, this temperature dependence can be ignored completely. This however is seldom the case. The temperature of the humidity sensors and the temperature sensor differ and this difference causes error in the humidity measurement. The difference is caused by different material properties and also by the placing of the sensors. This dilemma affects normal radiosonde application as well as dropsonde applications. But as the placing of the boom in both applications differ, the temperature difference between the sensors must be studied and measured and finally minimized. The dropsonde application should not bring additional error sources to the already sensitive measurement surroundings.

6.8.3 Pressure Sensor Accuracy

The pressure sensor operation is explained generally in 6.1.1.3. This pressure sensor type has a temperature dependence, which causes an error in the pressure measurement, but this dependence is removed by the use of separate temperature sensor right next to the pressure sensor. As the pressure sensor and the added temperature sensor are encased inside the transducer unit's metal cover, the two sensors have quite stabilized temperature environment. The next generation dropsonde application should not present any new features that would influence the temperature difference between these two sensors. One of these kinds of features could be the external heating of the modules and of the transducer unit module. If the applied heat is absorbed differently by the inside temperature sensor and the pressure sensor, additional error will occur in the pressure measurement. This has to be verified and studied in detail.

6.8.4 Wind Profile Accuracy

Wind solution technique is explained in 3.2. The next generation dropsonde application should not differentiate the use of the GPS module in relation to the radiosonde application and hence no additional errors are produced. The descent characteristics of the next generation dropsonde do influence the wind calculation, but this analysis concerns the parachute properties rather than the GPS module. The accuracy should remain the same or even improve in the dropsonde application, due to the fact that a radiosonde moves on a pendulum track while ascending. This motion is filtered out by the receiver system. In dropsonde application this motion does not exist and as such the wind solution does not has to be filtered or tempered with. This obviously improves the data quality and accuracy.

6.9 Design Specifications Conclusion

The above analysis states the main design specifications of the next generation dropsonde. This design set-up with all the different specifications having their own requirements is very much bound together. One specification affects the other. This setting is thus extremely affluent to compromise decisions. The best solution in one area may not work together with some other factor. Example on this is the amount of power installed in form of batteries. High power levels would definitely provide power for active heating elements in the dropsonde to account for the thermal tolerance problems, but it requires mass and volume, which in turn have to minimize. This situation can only be solved by analyzing each module's requirements and find the best solution that works for all. This design process begins with an initial configuration of the modules of the dropsonde. Each module is designed and tested keeping in mind the design specifications to come up with a solution. Then this solution is tested and analyzed and modified if the need arises.

This concludes the theoretical analysis of the thesis and marks the beginning of the next generation dropsonde testing and designing phase.

7. MODULE TESTS

The theoretical study of the next generation dropsonde requirements brought forward multiple factors that have to be taken into account. Theoretical calculations and studies can be used to analyze different requirements and to obtain estimates of the behavior of the system. Tests however form an essential procedure in gathering more precise and tangible data of the next generation dropsonde's behavior and thus contribute to the development phase.

The theoretical study suggested the worst case scenarios that the next generation dropsonde has to withstand and this has been used as a starting point in these module tests. Each of the next generation dropsonde modules is tested in various tests. These tests have been divided for each module and the test settings described. The test analysis will follow the description of the tests. The module tests include the following tests for individual modules

Table 4. Module Tests.

Module	Test
GPS	*Simulated drop sounding - TEST PLAN*
	Cold starting of the module - TEST PLAN
Transducer unit	Cold starting of the module
	Radiation error for T sensor
	Regeneration of U sensor
	Error caused by heating of the module
Power source	Cold starting of the module
	Warming of the module
	Voltage chopper operation
Transmission	Cold starting of the module
Parachute	Drop soundings
	Drag coefficient
Module Package	Heating of the modules

The worst case environment was chosen as 38 hPa of pressure and -72 °C of temperature. The decided pressure level is slightly lower than the planned operation pressure for

ICARUSS gondola of 100 to 50 hPa, but this difference was set to account for variations in the real life use. The temperature was set to -72 °C partly because this is a realistic worst case temperature encountered by the dropsonde and partly because the test machinery cannot produce lower temperatures. This environment was used in numerous tests and the environment was produced by WEISS 200 atmosphere chamber. The used reference measurements in various tests were conducted with Pt-100 temperature sensors, high precision humidity chambers with accurate reference meters and pressure reference. Tests that required special reference measurement are mentioned separately.

7.1 GPS Module Tests

Due to the fact that no prototypes of the GPS Module were available at the time period of this Master's Thesis, only the test designs are included here. These tests should be conducted for the GPS module, as it becomes available.

7.1.1 Dropsonde Sounding GPS Simulation

The operation of the GPS module in dropsonde soundings has to be verified. This can be conducted in a laboratory environment with a GPS simulator. This simulator can produce virtual motion by simulating the corresponding GPS satellite orientations. This data is then fed to the GPS module and its behavior analyzed.

The simulations should include different dropsonde soundings from altitude of 25 km and with various descend rates. Different wind conditions - horizontal movement of the dropsonde should also be applied. This kind of analysis has been conducted previously for the RD93 GPS module and the data and more especially the test scenarios designed should be used.

7.1.2 GPS Module Operation in Low Pressure & Temperature Environment

The GPS module should be placed in the worst case environment for different time periods and then turned on. By feeding the GPS simulator data to the GPS module, the behavior of the module could be compared against the test results obtained from laboratory conditions. This should differentiate the effect of the worst case environment.

7.2 Transducer Unit Tests

The measurement accuracy has to be maintained in the next generation dropsonde application and thus effort was put to conduct these tests as efficiently and accurately as possible.

7.2.1 Cold Starting of the Module

The effect of cold starting the transducer unit after long periods in low pressure and temperature conditions is one of the main concerns with the next generation dropsonde. As this high altitude platform takes the Vaisala sensors to an operational environment previously unexamined because of the long exposure times, this test accounts for as one of the most important tests. Long exposure to low pressure and temperature conditions can have unwanted side effects that have to be examined. Thus the cold starting of the transducer unit was tested.

The test was conducted in an atmosphere chamber with the pressure set to 38 hPa and the temperature to -72 °C. Several transducer units were kept in this environment for different periods of time, ranging from 3 hours to more than 2 days, and then switched on. Temperature and pressure sensor measurement was then compared to the reference meters to see if the dropsonde measurement had any error.

The above method was then compared with the results were the transducer units were kept on different periods of time - starting from room conditions to the worst case scenario conditions while continuously measuring. This way the difference between the cold started and the continuously measuring units could be detected.

Test Results

Cold starting of the transducer unit did not produce additional error. Starting the measurement after long periods in the worst case scenario did not differ from the measurements that were conducted continuously from room conditions to the worst case scenario. The differences in these two tests were minute and accountable for measurement general measurement error. *Table 5* contains the data gathered from these tests.

Table 5. Results of Cold Starting the Transducer Unit.

	3h duration	7h duration	52h duration	Continuous
Average T Difference [°C] 30 min period	-0.4226	-0.4714	-0.5636	-0.4562
Average P Difference [hPa] 30 min period	0.2703	0.2992	0.4078	0.07917
Difference T [°C]	**-0.0336**	**0.0152**	**0.1074**	0
Difference P [hPa]	**0.1911**	**0.2200**	**0.3286**	0

The most obvious reason for the fluctuations in the results was due to the fact that the temperature pressure chamber did not produce stable conditions in the chamber, but instead the temperature and the pressure inside the chamber fluctuated. These fluctuations were between ±0.5 °C and ±1 hPa. This steady sine-wave-like behavior produced error in both the reference measurement and the transducer unit sensor measurement due to the different time constants of the sensors. The reference sensors adapted to the change more slowly and hence error was produced.

The test however indicated that no major measurement error is produced by cold starting the transducer unit. More accurate measurements should however be conducted in more stabile environment to obtain more accurate data from the effect of cold start.

7.2.2 Radiation Error of Temperature Sensor

The accuracy requirements set by WMO requires that the next generation dropsonde must measure PTU and wind data according to their specifications. Thus different dropsonde configurations had to be tested against these requirements.

In a test, which measures the accuracy of a sensor, the reference to which the sensor is compared has an upmost importance. Since this test was conducted in a real life environment of above 20-km altitudes, the reference measurement had to be carefully examined. Since the behavior and errors caused in the temperature measurement of a Vaisala *radiosonde* are well established, the use of *radiosonde* as a reference was decided. Vaisala

RS90 radiosonde temperature measurement errors - caused by radiation and other factors described in 6.7.1 - are well analyzed and they lay the reference ground needed for the temperature measurement accuracy of the next generation dropsonde. This test was designed to find the differences between the detected temperature of the measured temperature in a *radiosonde* application and a dropsonde application.

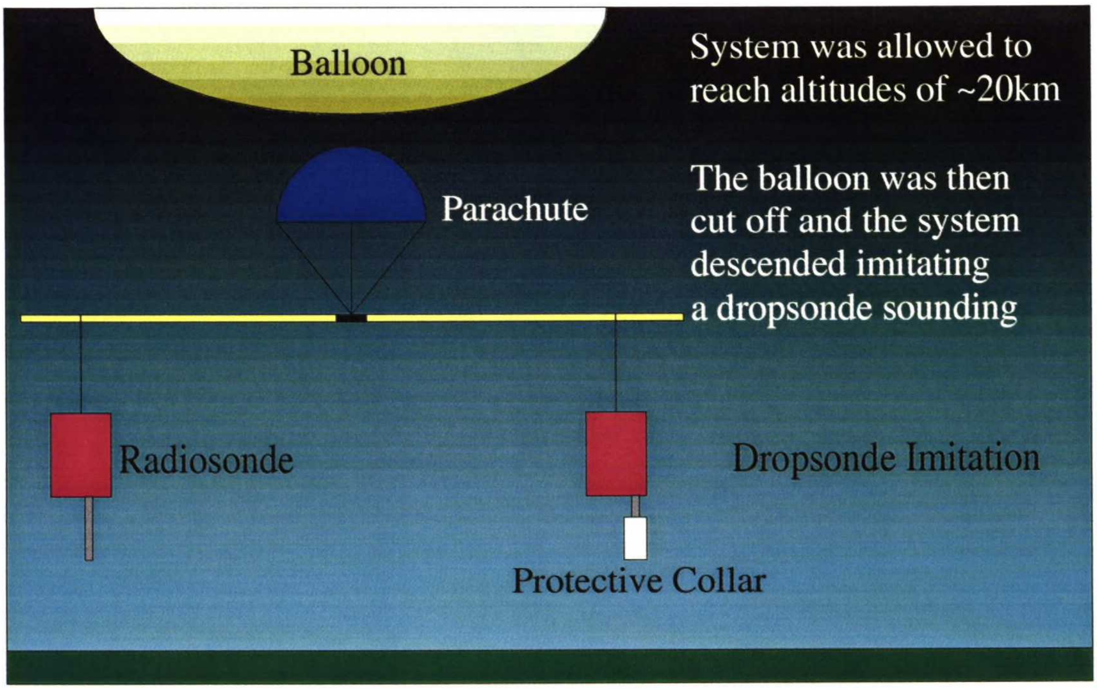


Figure 33. Temperature Sensor Radiation Error Test.

The test was conducted with a turned RS90 radiosonde attached to the end of a long pole. Another RS90 radiosonde - turned upside down equipped with a collar around the sensor boom to simulate a dropsonde - was attached to the other end of the pole. This system was then lifted to altitudes of ~20 km with helium filled balloon and released from the balloon with an electronic switch. The pole and the sondes attached to it were then allowed to descend to ground while measuring. The measuring data was collected and analyzed.

Using the raw data - data measured by the temperature sensor without any tempering or corrections - the differences between the two sondes could be detected. Since the behavior of the RS90 radiosonde temperature sensor measurement is well established, discreet behavior of the simulated dropsonde temperature sensor measurement can be calculated.

Test Results

This test failed to produce valuable data. The difficulties of obtaining data, after the system had ascended for more than one and a half hours and started to descend, proved to be unreliable. The telemetry between the sondes and the ground equipment did not operate reliably and thus no usable data was received. A drained or weak battery can explain this behavior after one and half hours of flight or the distance between the sondes and the receiver. All in all more careful examination of the system has to be conducted before new attempts are conducted.

The nature of this test is however of such importance that this should be conducted while developing the next generation dropsonde. Also simulated radiation experiments where the temperature sensor is radiated with and without a protective collar would give valuable input on the effects of the different sensor boom environments.

7.2.3 Regeneration of Humidity Sensor

Regeneration of the humidity sensors in low pressure and temperature is a requirement that the next generation dropsonde has to meet. One possibility is the use of contamination shield around the sensors prior the launch of the dropsonde, but this method faces other difficulties, such as the removal and the effectiveness of the shield. Thus regeneration at these conditions has to be tested.

7.2.3.1 Regeneration Test I

The humidity sensors were first regenerated in a ground check device. This ground check device consists of small chamber, which is filled with humidity and contaminant removing substance. The humidity sensors attached to the sensor boom were then inserted into this chamber and heated with 24V for a period of 5 minutes. This procedure is the standard regeneration procedure and it has been proven efficient. These purified sensors were then inserted into a high accuracy humidity chamber set to specific humidity levels. The sensor readings were compared with the humidity chamber reference humidities and the difference recorded. Next the same sensors were deliberately contaminated with high volatile Pentane in a closed container. The contamination could be observed as a reduction in the humidity reading as the sensors were once again placed in the same humidity chamber with same settings. After this, the sensors were placed in atmosphere chamber set to -72 °C and 38-hPa pressure. Here the sensors were then regenerated with 24V for 5 minutes and placed in the humidity chamber once more. The humidity readings were then measured and verified against the first test results to see if the sensors had indeed been purified by the regeneration.

Test Results

The regeneration was successful with the standard 24 Volts for 5 minutes in the worst case environment. All of the contaminated sensors were purified and no overheating of the humidity sensor dielectric occurred.

7.2.3.2 Regeneration Test II

Second phase of the regeneration tests was to examine the energy input of the regeneration process. As stated the standard regeneration process requires the heating of the humidity sensors, having a heating resistance of 1600 Ω, with 24 Volts for 5 minutes. This implies that

$$P_{heater} = \frac{U_{reg}^2}{R_{heater}} = \frac{(24V)^2}{1600\Omega} = 360mW \qquad (17)$$

of power is fed to the heating resistor. This power is maintained for 5 minutes, which equals

$$W = P_{heater}t = (360mW)(300s) = 108J \qquad (18)$$

of work. A test was then set up to examine the possibility of applying equal amount of work with lower voltage levels with longer periods of time and examine if the sensors would then regenerate efficiently. Again the same test procedure was conducted, with the exception that some of the sensors were regenerated with the standard 24V-5 minute run and others with lower voltage longer periods of time. Lowering of the voltage level was one of the requirements, since the next generation dropsonde cannot produce 24 Volts - given the power source module requirements. The tested voltage/time periods were

Table 6. Regeneration Variables.

Resistance	Voltage [V]	Power [mW]	Time [s]	Work [J]
1600	24	360.0	300	108
1600	12	90.0	1200	108
1600	9	50.6	2134	108
1600	5	15.6	6923	108

As seen from the *Table 6*, the heating resistance had to be used for nearly 2 hours with 5 Volts to apply the humidity sensor the same amount of work.

Test Results

Sensors that were regenerated with 24 Volts for 5 minutes were the only sensors that were purified by the regeneration. Thus **lowering of the regeneration voltage and compensating it with more regeneration time does not work**. A graphical presentation of the results is illustrated in the Appendix **[A7]**.

7.2.3.3 Regeneration Test III

The third regeneration test was conducted to verify the standard regeneration procedure and its functionality. Several sensors were again treated as described in Regeneration Test I, with the exception, that now different sensors were regenerated with the standard 24 Volts but with less time. Instead of five-minute regeneration, four, three, two and one minute regenerations were used together with the reference regeneration of 5 minutes. The main reason for this was to examine the relation between the work done on the sensor and the power input to the sensor.

Test Results

Lowering the regeneration time lower than 5 minutes works. Contaminated sensors, which were regenerated with 24 Volts with 4, 3, 2 and 1-minute regeneration times, were purified. **Each alternative produced sufficient regeneration of the humidity sensor.**

7.2.4 Error Caused by Heating of the Module

This test's goal was to quantify the amount of error produced by temperature gradient between the transducer unit and the sensor boom described in 6.1.2.

By heating the transducer unit and measuring its temperature against the temperature of the boom - the temperature measured by the temperature sensor - the temperature gradient can be calculated and the sensor errors detected.

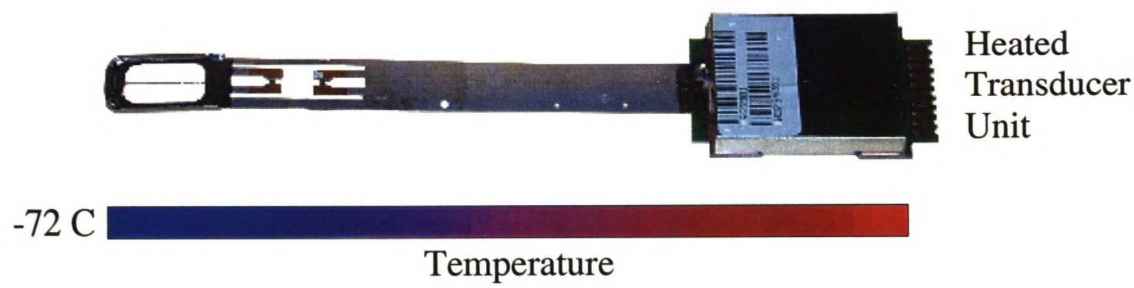


Figure 34. Temperature Gradient Created Over Transducer Unit.

This test was conducted to series of transducer units. The units were wrapped in insulating layer with a heating resistor attached to the transducer unit. A reference Pt-100 sensor was also installed inside the insulation to measure the transducer temperature. The whole unit was then set to an environment of normal pressure and -72°C and an extra Pt-100 sensor placed right next to the sensor boom. As the heating resistor was turned on, the transducer unit's temperature increased as the boom temperature remained lower. The effect on the sensor measurement was observed as the temperature gradient changed. Normal transducer units were also placed around the heated unit to compare the effect.

Test Results

The maximum temperature gradient between the transducer unit and the sensor boom was 90°C. At this temperature gradient, the transducer unit was heated to a temperature of +20°C while the boom remained at -72°C. Each of the three sensors - temperature, humidity and pressure - acted differently due to the temperature gradient. *Table 7* includes the averaged results.

Table 7. Transducer Unit Heating Results at 90 °C Temperature Gradient.

Sensor	Temperature [C]	Humidity [RH]	Pressure [hPa]
Averaged Measurement Difference between Heated and Non-heated Transducer Units.	0.31	2.75	0.46

The differences are quite extensive. Recalling the recommended accuracy values set by WMO in *Table 3*, these kind of deliberate errors in the measurements are not acceptable.

The main reason for this measurement difference is the heat conducted from the transducer to the boom and sensors. As stated the humidity sensor is temperature dependent and this affects the measurement. Transferred heat also affects the temperature sensor. Pressure sensor is equipped with its own temperature sensor located inside the transducer unit to minimize the temperature dependence of the pressure measurement. Thus no extra error should be implemented on the pressure sensor.

These values are not absolute error values, but rather values indicating the change that a 90°C temperature gradient creates in the measurements in comparison to measurements in zero temperature gradients. Absolute accuracy measurements in stable environment chambers with accurate reference measurement should be conducted in the development of the next generation dropsonde.

7.3 Power Source Tests

Power source testing aimed to find a suitable battery for the next generation dropsonde application. As the worst case environment at which the dropsonde has to reside was set to -72 °C and 38 hPa, the requirement for the battery to operate reliably was high. Commercial alkaline batteries do not specify operation temperatures lower than -20 °C and even the most specialized lithium batteries do not specify temperature limits below -60 °C. This situation initiated the idea of heating the battery. The power source tests included a test for cold starting different batteries and output current characteristics in worst case scenario and the heating of the batteries. The test batteries were all lithium based commercial batteries as indicated by *Table 8*.

Table 8. Power Source Test Batteries.

	Ultralife U9VL-J	SAFT LSH14	Duracell DL123
Type	Li/MnO_2	$Li/SOCl_2$	Li/MnO_2
Operating temperature (manf.)	-40 °C	-60 °C	-40 °C
Nominal capacity	1.2 Ah	5.5 Ah	1.4 Ah
Nominal voltage	9.0 V	3.6 V	3.0 V
Max recommended constant current	120 mA	800 mA	N/A
Diameter	26.3x17.3 mm (rect)	26.0 mm	16.9 mm
Height	48.7 mm	50.3 mm	34.5 mm
Weight	36.4 g	51 g	17 g

7.3.1 Cold Starting of the Batteries

Each battery was placed in the worst case scenario environment of -72 °C and 38 hPa and kept there for 40 hours - thus making sure that the batteries' temperature had been lowered to ambient. Then a resistive connection was coupled around each battery and the output voltage measured. The resistance was selected to create a ~100mA current which is an assumed current requirement during a sounding. This also meant that two batteries were connected in series to achieve higher that +5 V level - excluding the Ultralife battery. The behavior of the output voltage was measured through the entire test.

Test Results

The tests verified the assumption that lithium based batteries are the only option for the next generation dropsonde. Of the three lithium batteries only one operated sufficiently. The SAFT LSH14 was the only battery to provide any kind of reasonable voltage after long exposure to worst case environment. The other two batteries' output voltages dropped close to zero after the resistive load was connected where as the SAFT's output voltage decreased from the original 7.2 Volts (2*3.6 Volts - batteries in series) to an average of 5 Volts. *Table 9* categorizes the results.

Table 9. Power Source Test Results.

	Ultralife U9VL-J	SAFT LSH14	Duracell DL123
Original Output Voltage [V]	9.00	2 * 3.60	2 * 3.00
Average 30 min Output Voltage After 40h Exposure to Worst Case Environment [V]	0.28	5.14	1.10
Average Output Current [mA]	N/A	99...110	N/A

The average output voltage was calculated from the time the resistive load was connected around the battery up to a 30-minute period. After this time period the measurement was continued and the temperature gradually increased by +10 °C after every 40 minutes. The general trend on each battery was that the output voltage increased as a function of the temperature. Graphical results on the averaged behavior of each battery are included in the Appendix as follows

- Ultralife U9VL-J **[A8]**
- SAFT LSH14 **[A9]**
- Duracell DL123 **[A10]**

7.3.2 Warming of the Batteries

Given the extreme cold conditions, to which the batteries are exposed, the concept of heating the battery for higher output voltages was tested. Special heating foils embedded in flexible membrane were wrapped around the battery and heated with the battery itself. After 30 minutes warming period the batteries were connected to resistive loads chosen to drain ~100 mA current from the batteries. The output voltage was continuously measured.

Due to the weak performance of the Duracell and Ultralife batteries in the worst case environment, heating tests could not be conducted to them, but only for the SAFT battery. The output voltage of the other two batteries was so low that they could not produce power for the heating element.

Test Results

In this test, only one SAFT battery was used and the used heating elements were small 45 Ohm heating resistance element foils. The performance of the battery's output voltage was compared to a non-heated battery and the difference recorded.

Table 10. Battery Heating Test Results.

SAFT LSH14	No Heater	One Small Heater	Two Small Heaters
Original Output Voltage [V]	3.6	3.6	3.6
Heating Power [mW]	0	192	306
Current for the Heaters [mA]	0	65	117
Averaged Output Voltage After Heating Elements were shut [V]	2.745	2.806	2.956

As indicated by *Table 10* the output voltage was not increased greatly by the heating of the batteries. Extrapolating these results to a situation of having two batteries in series, the gain in the output voltage with two heaters would be + 0.422 Volts. This does not change the operation of the power source significantly and **thus it is recommended that extra heating elements around the SAFT LSH14 batteries are not needed.**

7.3.3 Voltage Chopper Operation

The best solution for the next generation dropsonde's power source is to use single SAFT LSH14 battery. This single battery has enough capacity to provide power for the dropsonde. The only thing lacking is the amount of voltage. As a single battery produces 3.6 Volts and on average 2.54 Volts after exposed to the worst case environment, the voltage levels are not adequate. Even with two batteries the voltage level should be increased. Thus the voltage has to be increased by voltage choppers and their behavior in the worst case environment has to be examined. The voltage chopper tests included four scenarios,

- Voltage chopper operation in room conditions with two SAFT LSH14 batteries
- Voltage chopper operation in -72 °C with two SAFT LSH14 batteries
- Voltage chopper operation in room conditions with outside power source
- Voltage chopper operation in -72 °C with outside power source

These four scenarios were designed to differentiate the performance of a Linear Technology LTC 1872S6 voltage chopper from the performance of the power sources and to further investigate the behavior of the voltage chopper in cold temperatures.

Test Results

Table 11. Voltage Chopper - Room Conditions - SAFT.

R [Ω]	V_{in} [V]	I_{in} [mA]	V_{out} [V]	I_{out} [mA]	P_{in} [W]	P_{out} [W]	η
15	5.81	1898	11.91	781	11.03	9.30	0.84
22	5.67	1707	13.57	600	9.68	8.14	0.84
33	5.95	1193	14.27	428	7.10	6.11	0.86
47	6.20	825	14.27	306	5.12	4.37	0.85
68	6.41	547	14.27	208	3.51	2.97	0.85
100	6.60	361	14.27	141	2.38	2.01	0.84
150	6.73	238	14.29	95	1.60	1.36	0.85

Table 12. Voltage Chopper in -72 °C - SAFT.

R [Ω]	V_{in} [V]	I_{in} [mA]	V_{out} [V]	I_{out} [mA]	P_{in} [W]	P_{out} [W]	η
15	N/A	N/A	N/A	N/A	N/A	N/A	N/A
22	N/A	N/A	N/A	N/A	N/A	N/A	N/A
33	N/A	N/A	N/A	N/A	N/A	N/A	N/A
47	N/A	N/A	N/A	N/A	N/A	N/A	N/A
68	1.9	1090	5.9	82	2.07	0.48	0.23
100	4.69	520	14.06	140	2.44	1.97	0.81
150	4.70	338	14.06	91	1.59	1.28	0.81

Table 13. Voltage Chopper - Room Conditions - Outside Power Source.

R [Ω]	V_{in} [V]	I_{in} [mA]	V_{out} [V]	I_{out} [mA]	P_{in} [W]	P_{out} [W]	η
15	N/A	N/A	N/A	N/A	N/A	N/A	N/A
22	7.2	1455	14.24	639	10.48	9.10	0.87
33	7.2	975	14.24	428	7.02	6.09	0.87
47	7.2	699	14.18	303	5.03	4.30	0.85
68	7.2	478	14.23	208	3.44	2.96	0.86
100	7.2	325	14.25	141	2.34	2.01	0.86
150	7.2	219	14.06	95	1.58	1.34	0.85

Table 14. Voltage Chopper in -72 °C - Outside Power Source.

R [Ω]	V_{in} [V]	I_{in} [mA]	V_{out} [V]	I_{out} [mA]	P_{in} [W]	P_{out} [W]	η
15	N/A	N/A	N/A	N/A	N/A	N/A	N/A
22	N/A	N/A	N/A	N/A	N/A	N/A	N/A
33	7.2	1020	13.93	416	7.34	5.74	0.79
47	7.2	710	14.02	301	5.11	4.22	0.83
68	7.2	480	14.08	206	3.46	2.90	0.84
100	7.2	330	14.04	139	2.38	1.95	0.82
150	7.2	220	14.04	95	1.58	1.33	0.84

The results indicate the amount of voltage and current driven into the voltage chopper and the voltage and current received from the voltage chopper. The output voltage was set to 14.0 V level, but as indicated by the results, this level could not always be reached. The efficiency of the voltage chopper and the power source used is included in the results.

The test indicates that the voltage chopper system used together with SAFT batteries cannot produce more than ~150mA of current in the worst case scenario - *Table 12*. With this output current the chopper is draining the SAFT batteries with more that half an ampere of current. As soon as the current from the batteries is increased close to one ampere, the SAFT battery seems to decrease its output voltage. This results in the failure of the voltage chopper performance.

With the outside power source the voltage chopper could not produce more than ~400 mA of output current with already deteriorating efficiency - *Table 14.*

The performance of the voltage chopper with the SAFT batteries is rather limited. This is the case with the outside power source as well. The use of voltage choppers in the next generation dropsondes thus windows the maximum constant current available for the dropsonde modules. According to these test results, the maximum constant current consumption with two SAFT LSH14 batteries is around 150 mA. A number of different voltage choppers should however be tested to verify this current limit. Individual heating of the voltage chopper's components could also improve the performance.

7.4 Transmission Module Tests

Transmission module and especially its oscillator crystal were tested in low temperature conditions. The test included three different crystals that were commercially available and suitable for the next generation dropsonde application.

7.4.1 Cold Starting of the Transmission Module

The crystals' used in the transmission module represented similar oscillating specifications. The specifications are included in *Table 15.*

Table 15. Tested Crystals.

	Seiwa XM-1T	Hosonic 7SB	TeleQuartz CS10A
Frequency [MHz]	16.3676	16.3676	16.3676
Operating temperature range	+85°C to -40°C	+85°C to -40°C	+85°C to -40°C
Temperature stability at +85°C to -40°C	±15 ppm	±10 ppm	±15 ppm

The worst case scenario environment was used with the mentioned crystals. The crystals were placed in -72°C conditions for 40 hours and their frequency output measured continuously.

Test Results

As soon as the temperature began to decrease, so did the output frequency. *Table 16* contains the data.

Table 16. Transmission Crystal Frequency Test Results.

	Seiwa XM-1T	Hosonic 7SB	TeleQuartz CS10A
Original Frequency [Hz]	16 367 600	16 367 600	16 367 600
Average Frequency at -72°C [Hz]	16 369 544	16 369 140	11 901 027
Standard Deviation of the Frequency [Hz]	34.06	20.55	2 781 545.14

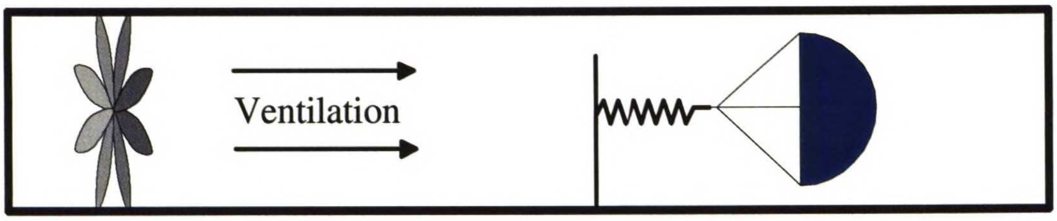
As *Table 16* indicates, **Seiwa and Hosonic crystals performed flawlessly in the worst case scenario environment, whereas the TeleQuartz crystal did not function at all.** The standard deviation of the first two was only ~30 Hertz and for the TeleQuatrz 2.8 MHz. Seiwa and Hosonic crystals meet the requirements set by the next generation dropsonde.

7.5 Parachute Tests

Parachute tests were conducted to gain understanding on the nature of different parachutes. The whole concept of using a parachute was also under study. This test used the theoretical calculations of the terminal velocity properties of different dropsonde packages ranging from sondes using large square cone parachutes to dropsonde with no parachute at all. This theory was then compared to actual RD93 dropsonde soundings made with a small square cone parachute.

7.5.1 Drag Coefficient Tests

The drag coefficients of different parachutes were measured in a wind tunnel. Using the equations derived earlier, the drag coefficient was calculated for various parachute types. The tested parachutes were placed in different air velocities and the drag force thus created was measured with a scale spring. *Figure 35* illustrates the setting.



$$F_{Drag} = F_{Spring} = k(x_s - x_0) \Rightarrow C_D$$

Figure 35. Drag Coefficient Measurement.

Test Results

Altogether three parachutes were tested in the wind tunnel. The drag coefficients were calculated using *Equation 12* for multiple ventilation velocities and their respective drag force.

Table 17. Drag Coefficient Test Results.

	Small Square	Mid Square	Large Square
Projected Surface Area [m^2]	0.09	0.13	0.36
Averaged Drag Coefficient	0.32	0.33	0.55

The small and mid sized parachutes produced a similar drag coefficient, whereas the largest parachute failed to follow the same pattern. The reason for this was in the size of the parachute. The largest parachute filled the wind tunnel almost completely and thus compromised the air flow properties. Thus the result is rather poor. But as the two different parachutes - same shape, different size - produced same drag coefficients, this results can be accepted as a reference drag coefficient for the square cone parachutes illustrated more closely in *Figure 36*.

This result was then implemented on the parachute theory to compare the different descend velocities of a RD93 dropsonde with three parachutes and also to a free falling RD93 dropsonde. The drag coefficient for the free falling dropsonde was taken as an average from different tables indicating the drag coefficients for a cylindrical tube. Multiple RD93 soundings that used small square parachute are included in the analysis as a reference. A graphical presentation of the results is included in Appendix **[A11]**. Included in the analysis is the data collection rate for each descend type at 2 Hz.

Figure 36. RD93 Small Square Cone Parachute Filled with Ram Air.

The graph indicates that the present RD93 dropsonde with a small square cone parachute has a total drag coefficient of 0.53 - calculated from the white best-fit line illustrated in **[A11]**. This account for the drag produced by a small square cone parachute and the RD93 dropsonde itself. As seen from the graph, the difference between the best-fit line and the theoretical descend of a small square cone parachute is caused by this difference in the used drag coefficient - 0.53 versus 0.32. Thus the theoretical descend velocities illustrate the difference between the parachutes.

The RD93 best-fit line produces a descent velocity of ~12 m/s at sea level and ~57 m/s at 30 km. The corresponding data resolution at 2 Hz can also be seen. For a free falling RD93 dropsonde - with an averaged drag coefficient of 0.86 - to obtain the same data resolution, the frequency of the measurement should be increased to 7.6 Hz. A requirement worth studying.

These results indicate the different descend velocities that the next generation dropsonde will experience with different parachutes. The reason to analyze RD93 descend was due to the real life data, which was readily usable as a reference. For the next generation dropsonde, the mass will be reduced from that of RD93, which slows the descend rate. Thus similar analysis must be done for the next generation dropsonde as soon as the mass of the sonde is determined.

7.6 Module Package

These module tests included one test on which the interior modules of the next generation dropsonde were simulated by cut circuit boards. This construction was built according to the discussion in Chapter 6.1.7 to test the possibility of heating all of the modules inside the dropsonde.

7.6.1 Heating of the Modules

The non-functional modules were piled on top of each other with a space left between each one. Heating elements were then placed on top of and below the package. Another configuration consisted of a heating element wrapped around the whole module package. A Pt-100 sensor was placed at the middle of the modules. This system was then covered with insulative layer and taped shut and placed into a cardboard tube. The system was again placed at -72 °C and 38 hPa and different power levels were used from outside power source to heat the module package and the corresponding temperatures inside the module package were measured. The purpose was to determine the needed power to raise the inside temperature to reasonable level. Temperature increases of +50 °C to +70 °C were seeked to reach close to zero degree temperatures. *Figure 37* illustrates the setup.

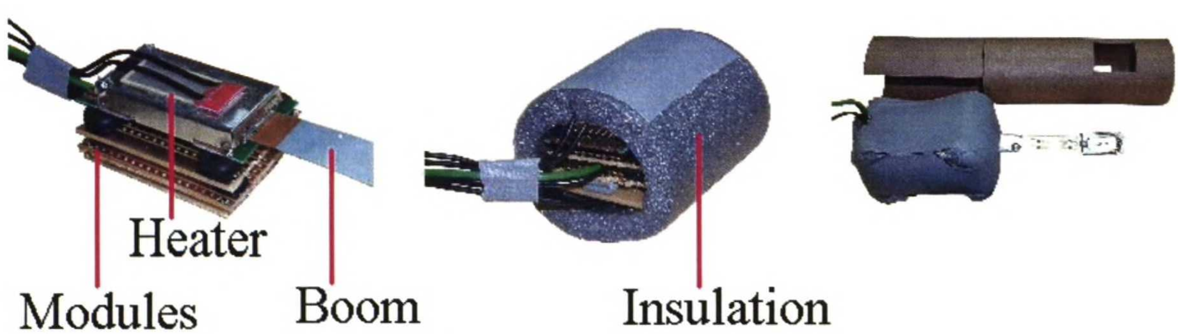


Figure 37. Dropsonde Inside Temperature Test.

The used power levels in the module heating test were 3, 2.5, 2, 1.5 and 0.5 W. Each of these power levels were used to heat both heating package configuration. The dropsonde package was first let to freeze in the worst case environment for one hour - so that the inside temperature decreased close to ambient - and then the power was fed to the heating elements for half an hour to obtain the maximum inside temperature. After this cycle the dropsonde package was again let to freeze close to the ambient temperature for an hour and then heated with alternative power level for half an hour.

Test Results

The following includes the tabular presentation of the results and the graphical presentation is included in **[A12]**.

Table 18. Dropsonde Inside Temperatures.

Type	Heating Power [W]	Increase in Inside Temperature [C]	Current Required with 5V power source [mA]
2 Small Heaters (Fig.33)	3.0	71.9	600
2 Small Heaters (Fig.33)	2.5	60.4	500
2 Small Heaters (Fig.33)	2.0	49.4	400
2 Small Heaters (Fig.33)	1.5	42.5	300
2 Small Heaters (Fig.33)	0.5	18.5	100
Large Heater	3.0	64.2	
Large Heater	2.5	55.3	
Large Heater	2.0	46.1	
Large Heater	1.5	39.5	
Large Heater	0.5	16.8	

To reach temperature increases of 70...50°C the dropsonde interior must be heated with 2.5 to 3 W power. The worst case temperature has been set to -72°C and thus with these power levels the dropsonde interior temperature could be increased to zero degrees - a temperature in which all the electronics and other components can operate reliably.

7.7 Test Conclusion

The conducted tests' primary function was to establish the test procedures for all of the modules and components of the next generation dropsonde. In addition, the first sets of data received from these tests are important for the design of the first prototype dropsonde. A short summary on each module is included here, which accounts for the best option if available and suggests optional solutions. Also included is a mechanical prototype design that has been built according to the specific sizes of the different modules. This prototype is included in *Figure 37.*

7.7.1 GPS Module Conclusion

- Code correlating GPS module
- Helix antenna

Code correlating GPS module is necessary to avoid unwanted GPS tracking problems especially in hurricane soundings. Helix antenna should be used for better performance over patch antenna. However if the size of the helix antenna creates problems, patch antenna should be considered.

7.7.2 Transducer Unit Conclusion

- Standard Vaisala transducer unit
- Fast response temperature sensor and humidity sensors
- Low heating resistances for humidity sensors

The standard transducer unit performed well in the initial tests. Care should however be taken when considering the heating of the interior parts of the dropsonde. Transducer unit should be isolated from this extra heating. Fast response temperature sensor is needed to obtain data at adequate rate from the very beginning of the sounding. The same applies to the humidity sensors. This requirement derives from the fact that the descend velocity of the dropsonde at high altitudes is quite extensive and so the sensors must be fast enough to compensate this. The data resolution should not be reduced due to slow reacting sensors. Due to the fact that the power source installed together with the voltage chopper cannot produce voltages of +10 V the humidity sensors need lower heating resistors to create sufficient regeneration power and heating levels.

7.7.3 Plug In Conclusion

- As simple as possible

Either optical or galvanic. Care must be taken in order to guarantee the flawless detachment of the galvanic connection upon dropsonde launch.

7.7.4 Power Source Conclusion

- One SAFT LSH14 battery

SAFT is the only power source that meets the requirements. One battery is sufficient to provide power for the entire dropsonde. Voltage choppers are however needed to increase the voltage. If high voltages - in excess of 12 V - are needed, two SAFT batteries are needed to produce the high voltage. This should however be avoided, since an additional battery introduces numerous disadvantages including extra price, weigh and size.

7.7.5 Transmitter Module Conclusion

- Transmitter module equipped with either Hosonic or Seiwa oscillating crystal

Other options can be considered, but their performance must be studied to avoid Telequatrz type behavior.

7.7.6 Parachute Conclusion

- Square cone parachute

If the data measurement rate can be increased to compensate faster descent rate, free falling dropsonde should be considered. Streamers or alike should then be installed. Then the cost of the parachute could be reduced.

7.7.7 Additional Modules

- Insulation
- Heating

Insulation with styrofoam or substances alike styrofoam would provide thermal insulation, which is needed if heating elements are placed inside the dropsonde. Insulation or other stuffing inside the dropsonde will also embrace the modules for better shock absorption.

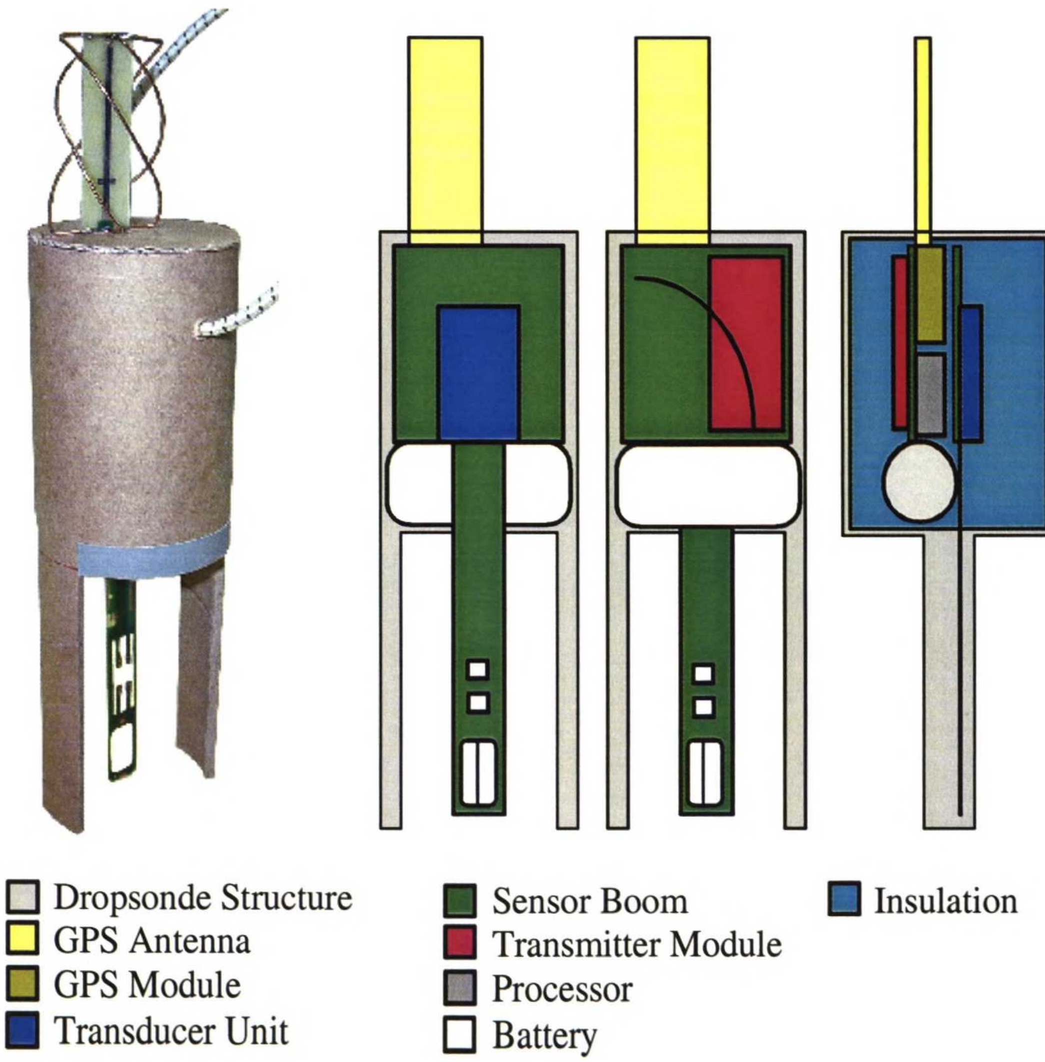


Figure 38. Next Generation ICARUSS Dropsonde Mechanical Design Idea.

The built mechanical design idea includes all the modules in their presumed size. The built mechanical prototype weighs 175 g and measures 26 cm in height and 3.5 cm in radius. The power source used is a single SAFT LSH14 battery. The voltage chopper option can be implemented on the transducer unit circuit board with all the rest additional features, such as internal heating of the dropsonde. Insulation covers all the modules, except the sensor boom, which is located outside the body. The body itself has been shaped to reduce the radiation error emitted by the body parts due to the lack of full protective collar. The temperature and humidity sensors do not have direct contact to this emitted radiation. The GPS antenna used is a helix antenna that requires lot of space, but the antenna has been taken outside the dropsonde body for better compactness and insulation for the other modules. The parachute attachment is used on both sides of the dropsonde's body.

According to the test results, a functional prototype can be built that meets the requirements of an ICARUSS platform dropsonde. This is an important fact and it helps to have a firm starting point in the future dropsonde design. As the results indicate, an option was found for each module that elementarily meets the requirements of the ICARUSS platform. From this setting more detailed testing and designing phase must be implemented that focuses on more precise testing and includes the requirement of cost-efficiency.
Further testing and analysis on the final ICARUSS dropsonde has to be conducted in order to find the optimal solution. The results and recommendations for each module included in the module test conclusion should lay ground for the initial design phase.

8. CONCLUSION

This Master's thesis examined the factors that have to be taken into account in the design of a next generation dropsonde for ICARUSS high altitude platform. The main focus was in the theoretical analysis of the environment and its effects on the dropsonde itself. Various tests were also designed and conducted to verify the theory and to gain more precise understanding of the requirements.

This Master's thesis included a short introduction to the aspects of the thesis. A general description of a dropsonde and an illustration of the building blocks of a dropsonde followed. A general overview on different platforms with a detailed analysis of an ICARUSS platform laid the ground for the requirements set by an ICARUSS platform on the next generation dropsonde. Series of tests were also included. The goals of this Master's thesis were to

- Understand the requirements set by an ICARUSS high altitude platform
- Analyze the requirements
- Test the requirements
- Find concrete solutions for the next generation dropsonde

These goals were covered in the chapters mentioned and the thesis was concluded with a few detailed solutions that were chosen as the most suitable for the next generation dropsonde. In addition, the established test procedures for the full development of the next generation dropsonde contributed as much as the initial results and solutions did. These test procedures should therefore be used in the future development of the next generation dropsonde for ICARUSS high altitude platform.

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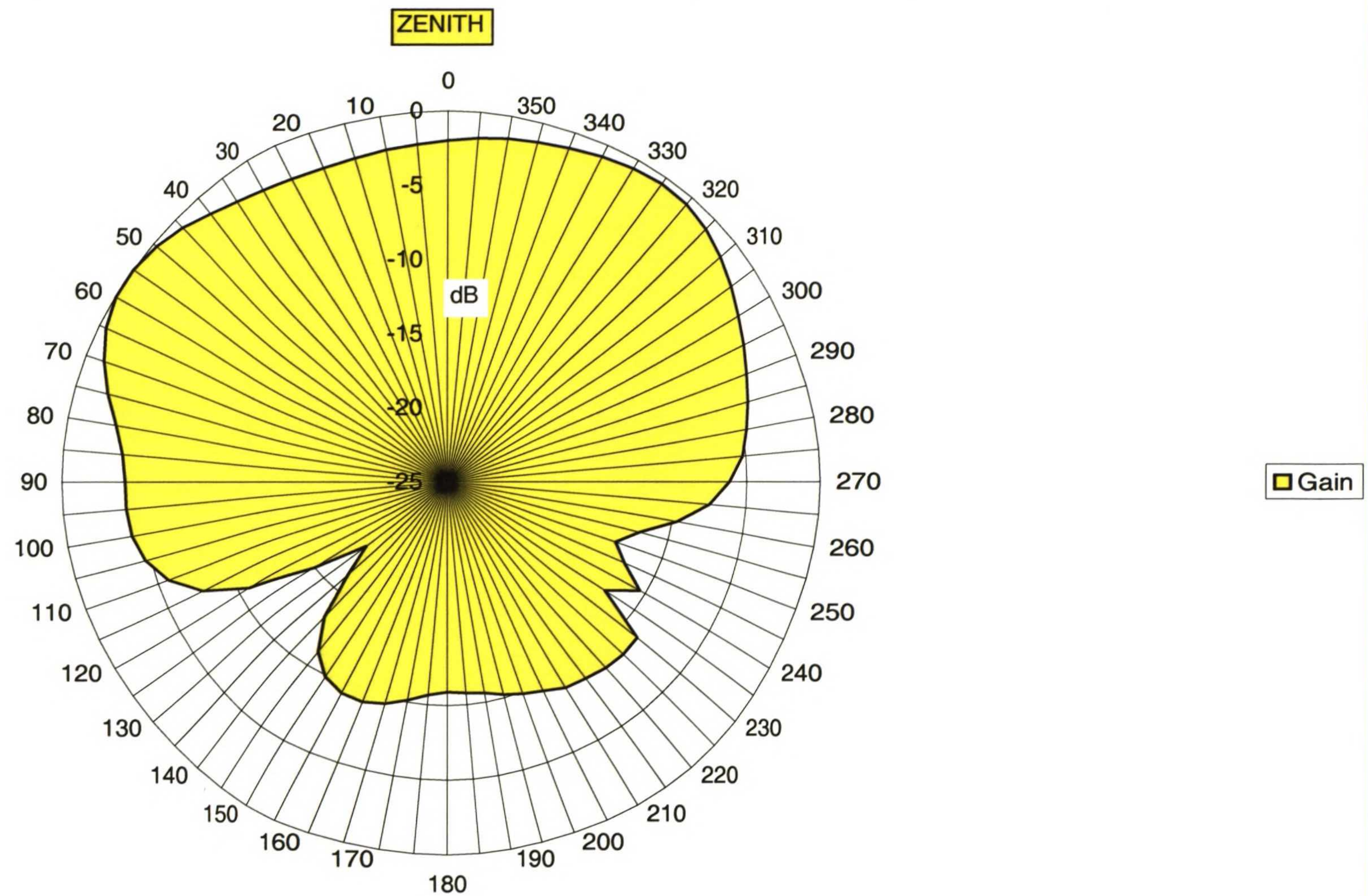
APPENDICES

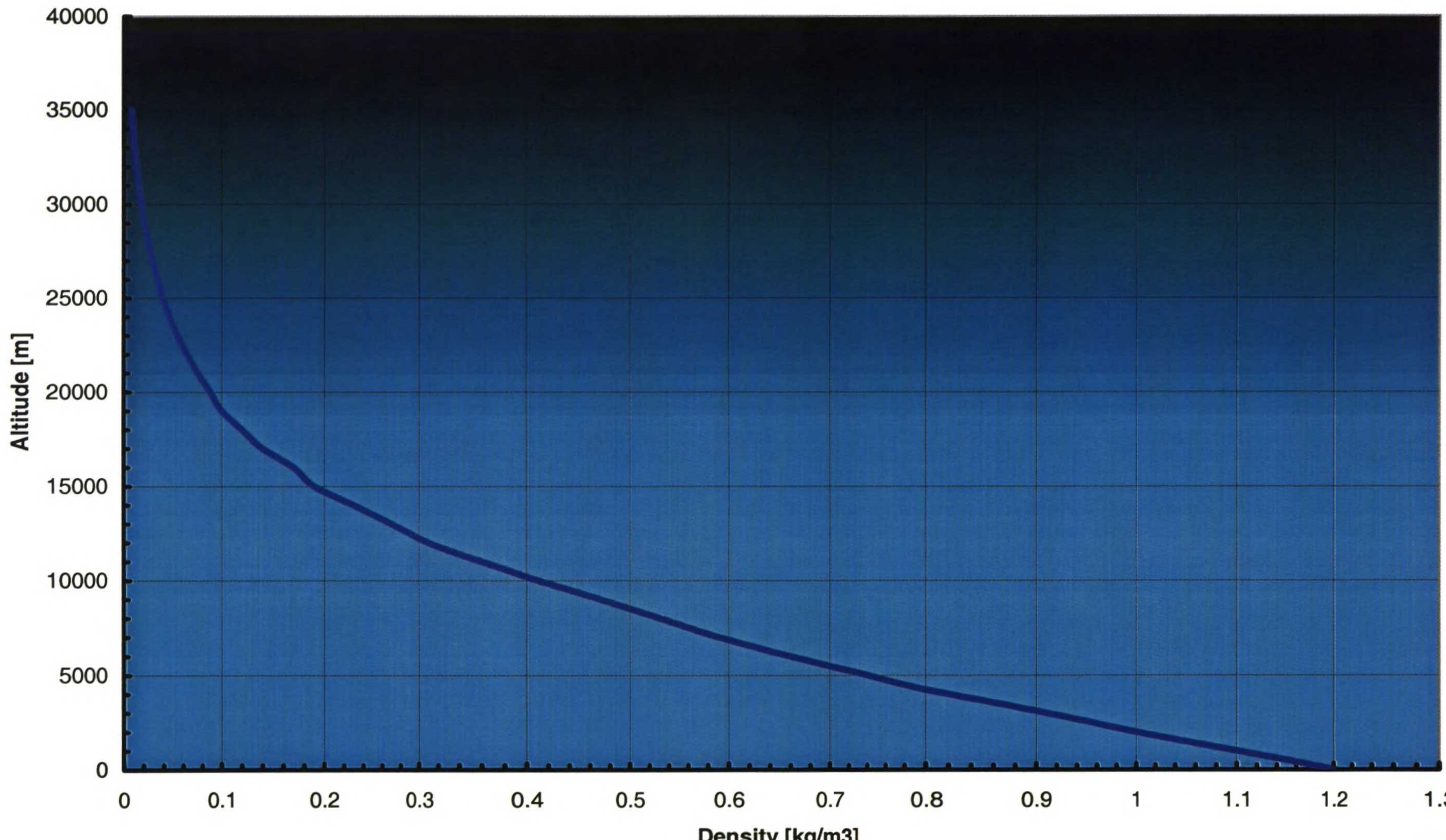
[A1] RD93 Technical Data Sheet

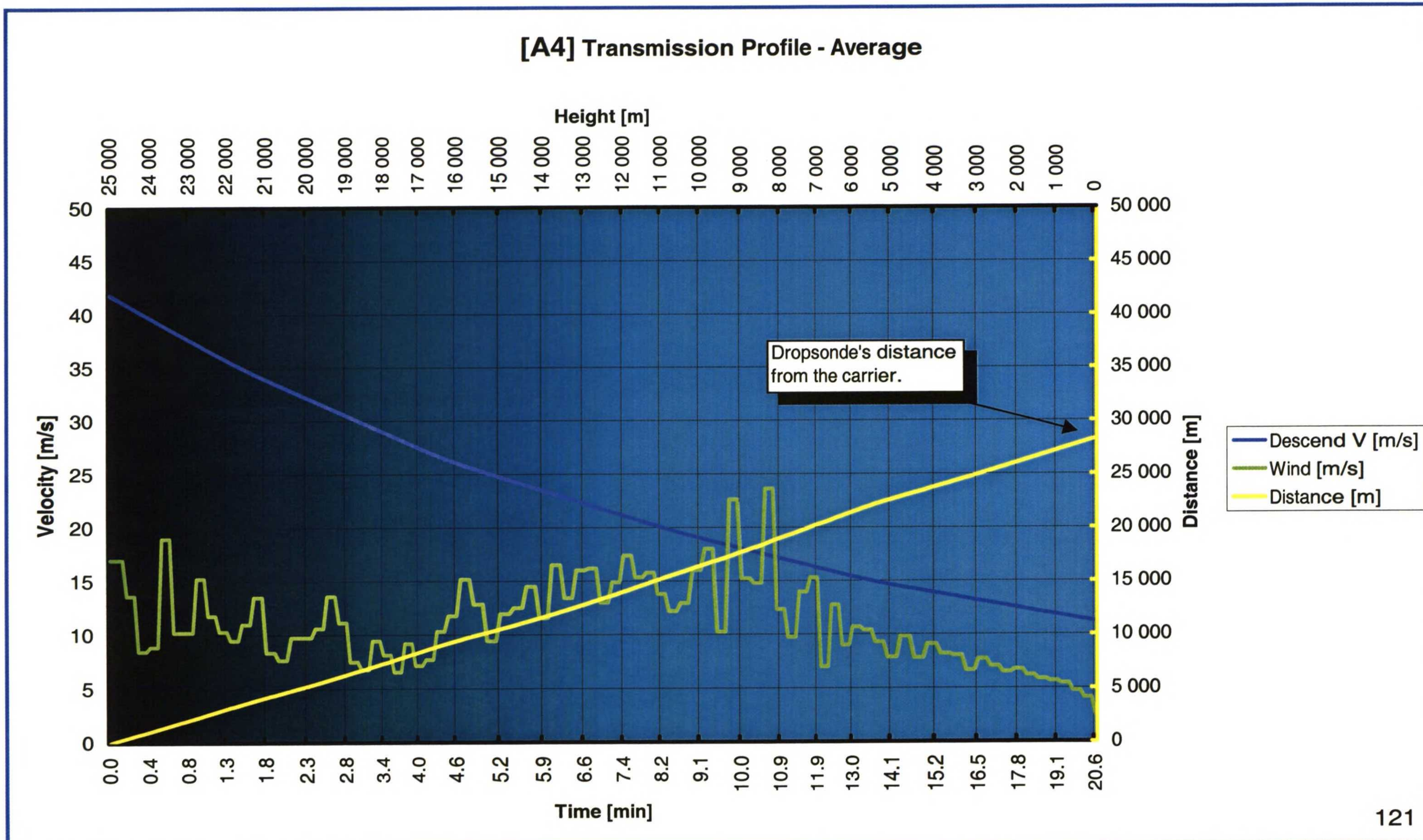
Chassis Interface		TTL Interface
GPS Receiver Channels		Track up to 8 satellites simultaneously
Transmitter		
	Frequency range	400 MHz to 406 MHz
	Frequency stability	± 3 kHz
	RF Power output	100 mW
	Harmonic output	> 50 dB below the carrier level
	DC input current	~225 mA at +15 V DC
	Digital deviation	> 2 kHz, < 2.5 kHz
	GPS diviation	> 2 kHz, < 2.5 kHz
	Total modulation	> 2.5 kHz, < 3.5 kHz
Battery		
	Type	Lithium, six CD-2 cells
	Voltage	+ 15 V
	Life	2 hours (operating), 3 years (shelf)
Pressure sensor		
	Range	1080 hPa to 100 hPa
	Resolution	0.1 hPa
	Accuracy	
	Repeatability	0.4 hPa
	Uncertainty	1.5 hPa
Temperature sensor		
	Range	+ 60 °C to - 90 °C
	Resolution	0.1 °C
	Accuracy	0.2 °C
	Repeatability	0.1 °C
	Uncertainty	0.5 °C
Humidity sensor		
	Range	0 to 100 RH
	Resolution	1 RH
	Accuracy	
	Repeatability	2 RH
	Uncertainty	5 RH
Horizontal winds		
	Range	0 m/s to 200 m/s
	Resolution	0.1 m/s
	Accuracy	0.5 m/s
Antenna		
	400 MHz impedance	50 Ω
	Wavelength	1/4
	Polarization	Vertical
Data rate		
	PTU	2 Hz
	Wind	2 Hz
	Descend speed	~11 m/s at sea level. See also **[A11]**

[A2] RD93 DropSonde Averaged GPS Helix Antenna Gain Pattern

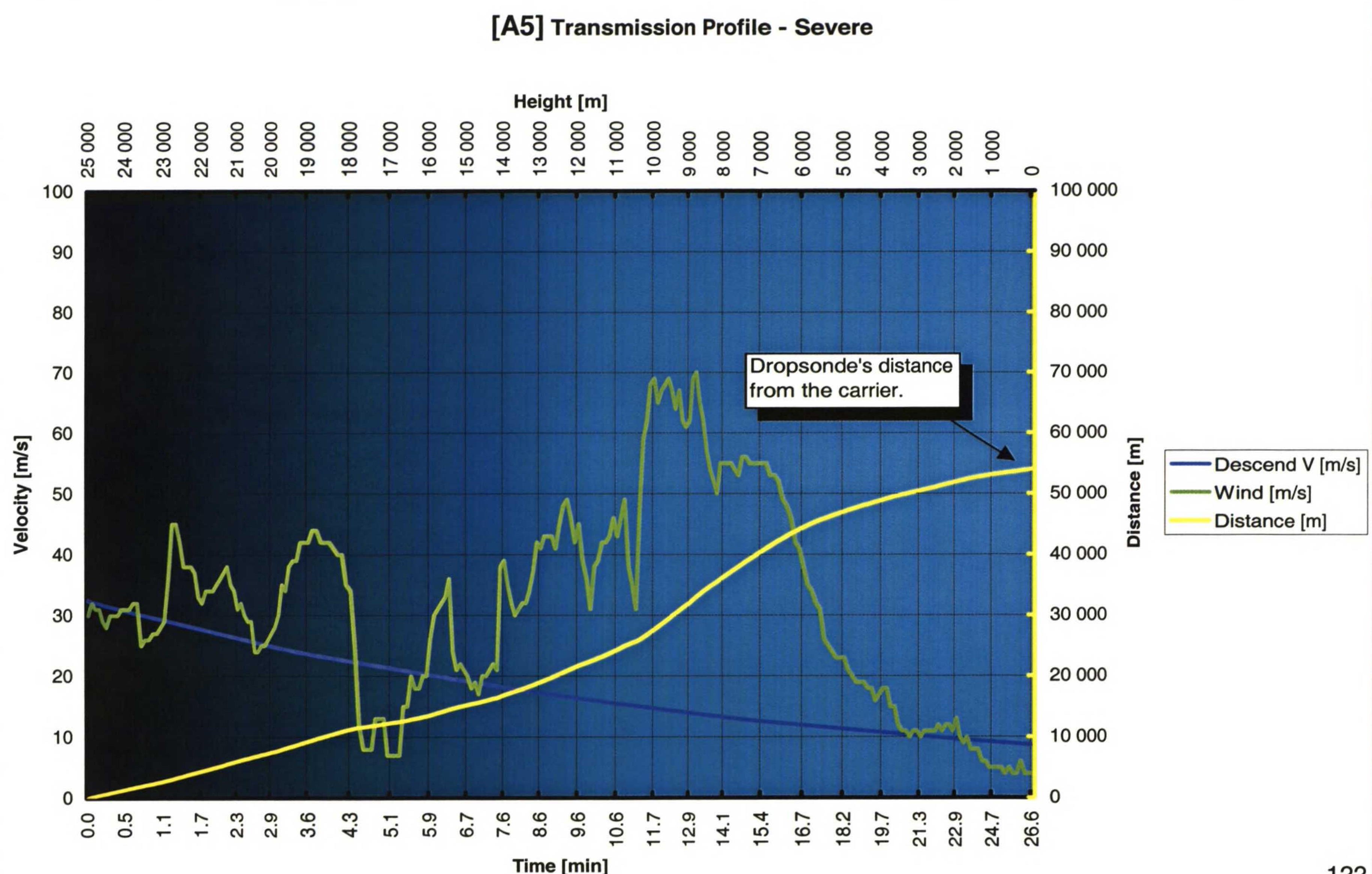


[A3] US Standard Atmosphere

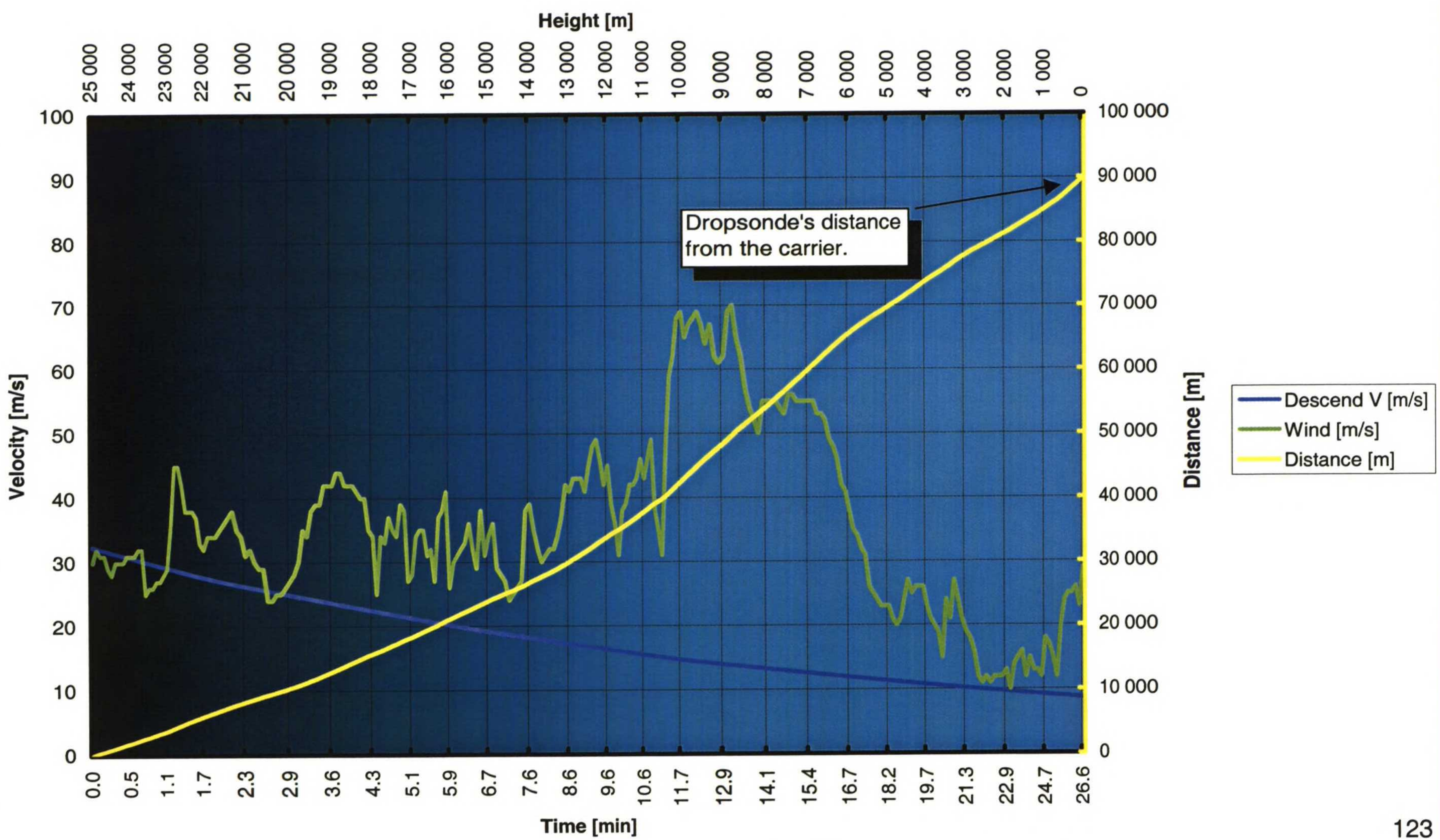


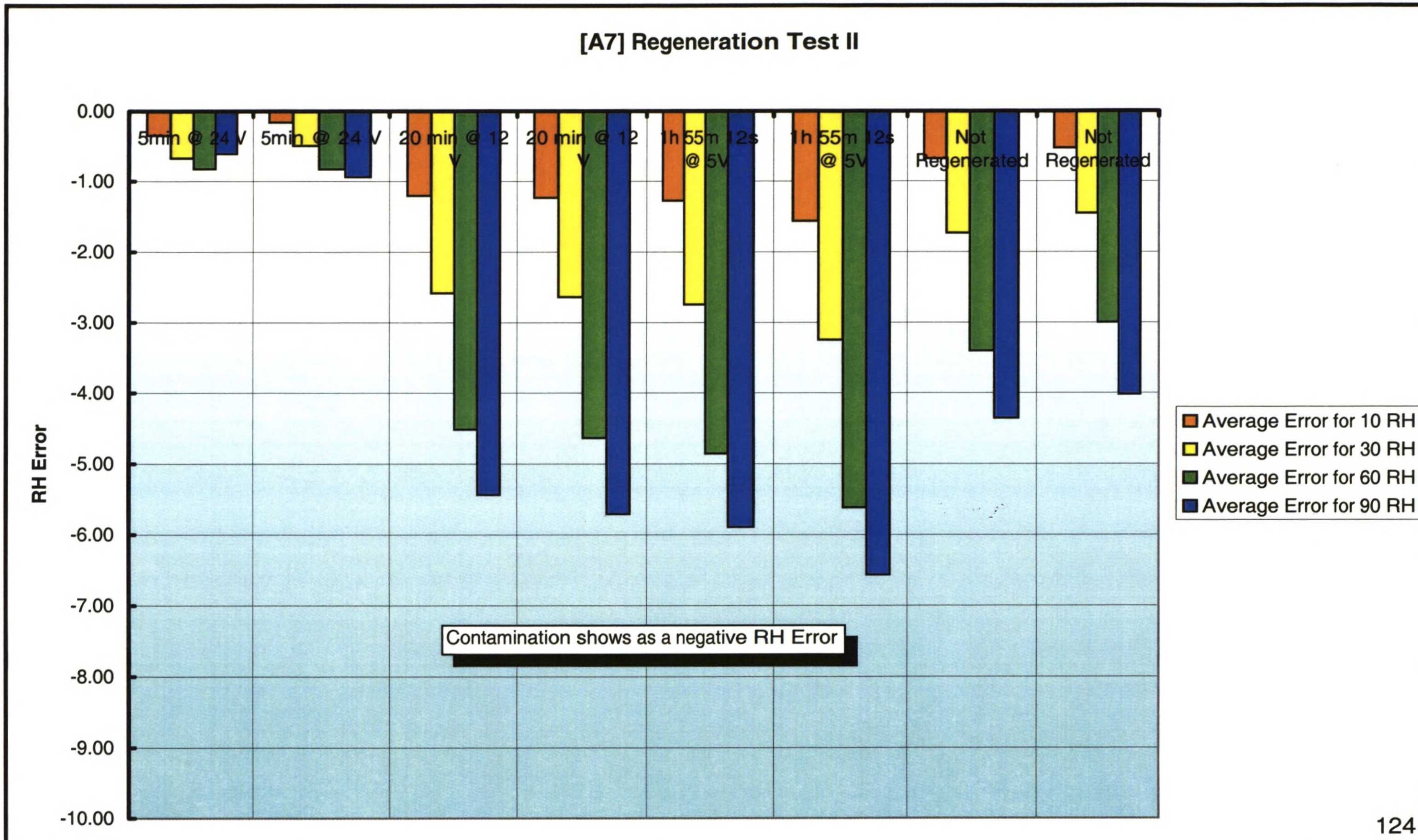


[A4] Transmission Profile - Average
Height [m]
25 000
24 000
23 000
22 000
21 000
20 000
19 000
18 000
17 000
16 000
15 000
14 000
13 000
12 000
11 000
10 000
9 000
8 000
7 000
6 000
5 000
4 000
3 000
2 000
1 000
0
Velocity [m/s]
50
45
40
35
30
25
20
15
10
5
0
Distance [m]
50 000
45 000
40 000
35 000
30 000
25 000
20 000
15 000
10 000
5 000
0
Time [min]
0.0
0.4
0.8
1.3
1.8
2.3
2.8
3.4
4.0
4.6
5.2
5.9
6.6
7.4
8.2
9.1
10.0
10.9
11.9
13.0
14.1
15.2
16.5
17.8
19.1
20.6
Dropsonde's distance from the carrier.
Descend V [m/s]
Wind [m/s]
Distance [m]


[A5] Transmission Profile - Severe
Height [m]
25 000
24 000
23 000
22 000
21 000
20 000
19 000
18 000
17 000
16 000
15 000
14 000
13 000
12 000
11 000
10 000
9 000
8 000
7 000
6 000
5 000
4 000
3 000
2 000
1 000
0
Velocity [m/s]
100
90
80
70
60
50
40
30
20
10
0
Distance [m]
100 000
90 000
80 000
70 000
60 000
50 000
40 000
30 000
20 000
10 000
0
Dropsonde's distance from the carrier.
Time [min]
0.0
0.5
1.1
1.7
2.3
2.9
3.6
4.3
5.1
5.9
6.7
7.6
8.6
9.6
10.6
11.7
12.9
14.1
15.4
16.7
18.2
19.7
21.3
22.9
24.7
26.6
Descend V [m/s]
Wind [m/s]
Distance [m]

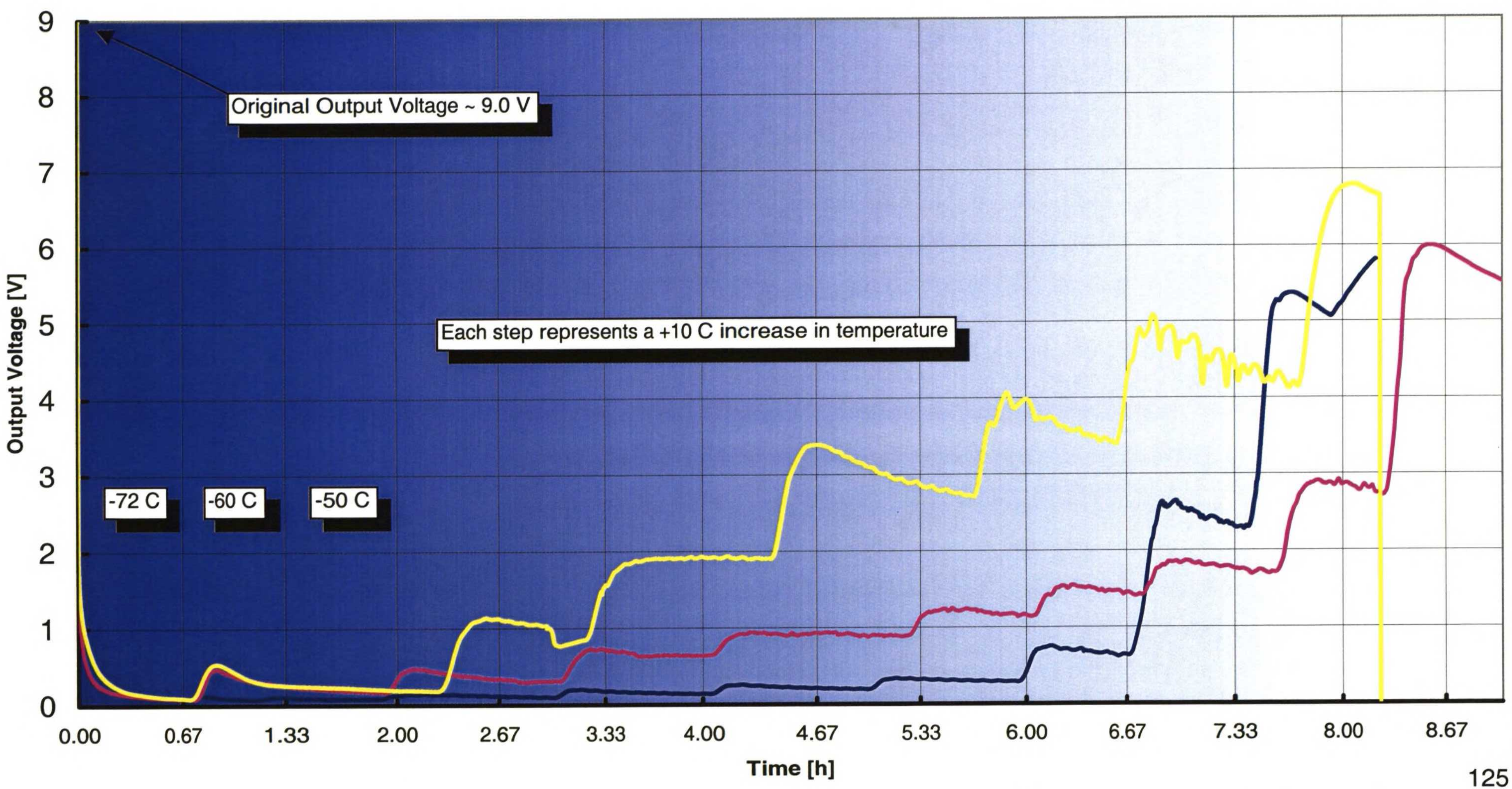
[A6] Transmitter Profile - Absurd (Gondola moving away with 20m/s velocity)



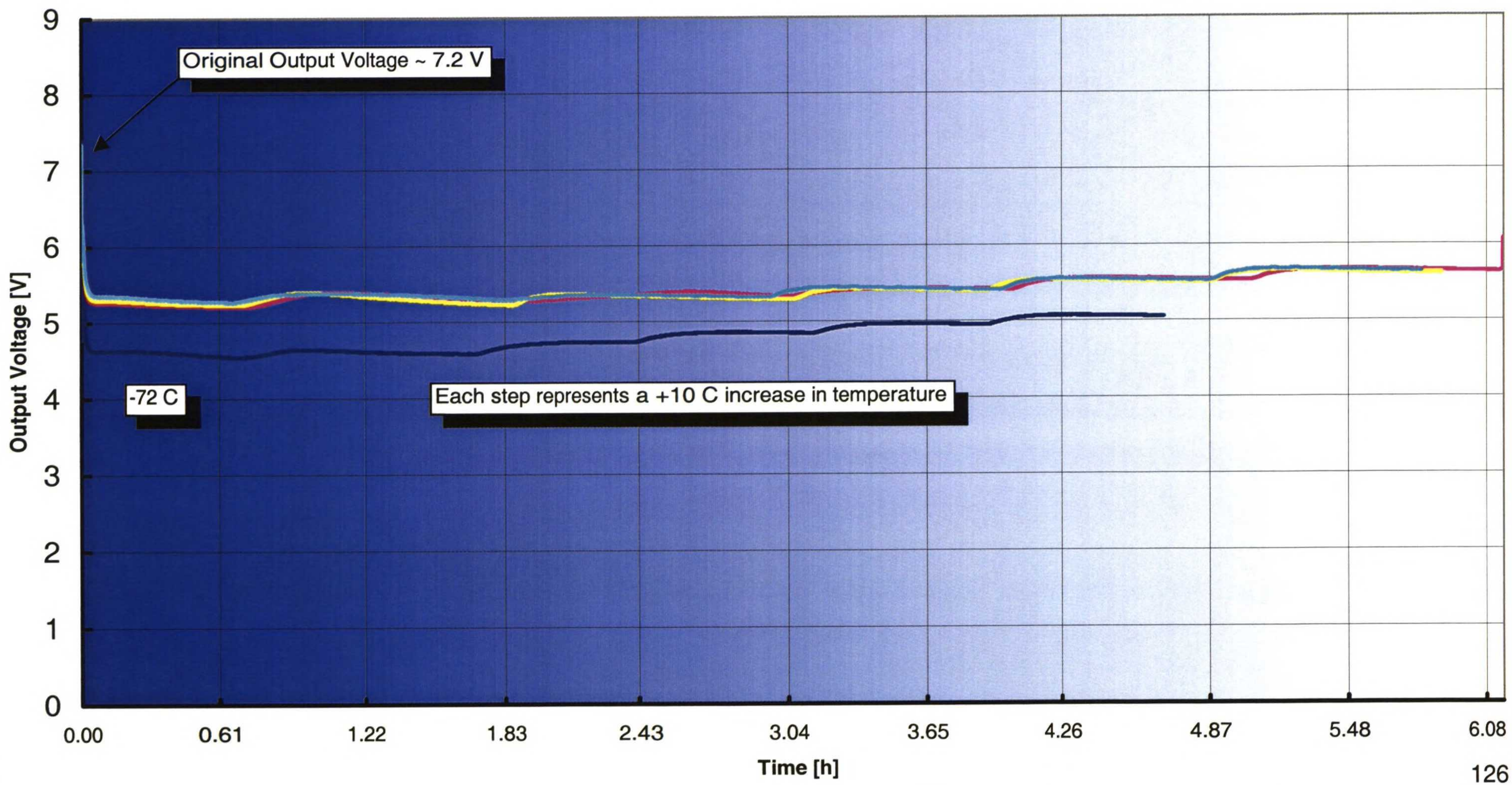


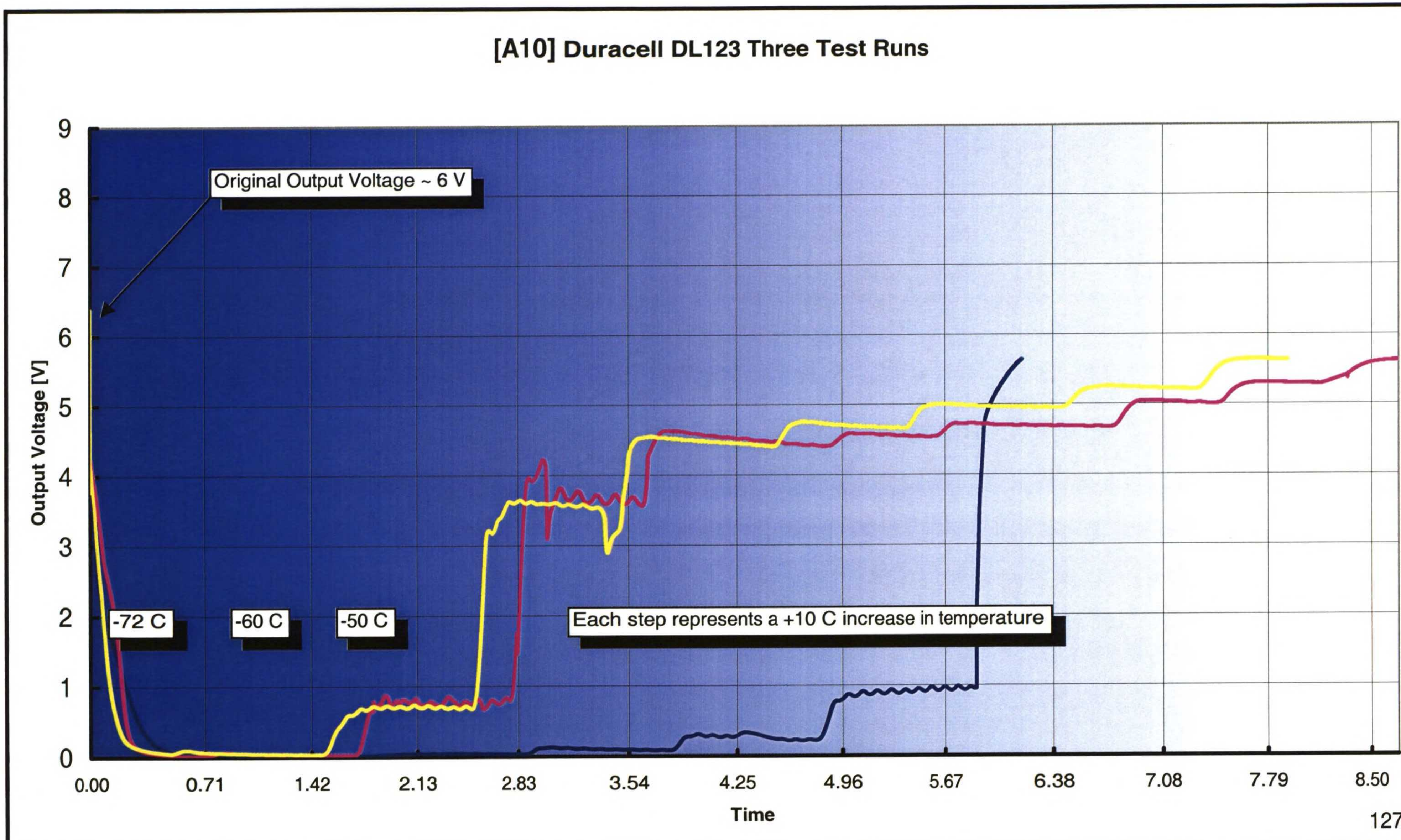
[A7] Regeneration Test II
RH Error
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
5min @ 24 V
5min @ 24 V
20 min @ 12 V
20 min @ 12 V
1h 55m 12s @ 5V
1h 55m 12s @ 5V
Not Regenerated
Not Regenerated
Contamination shows as a negative RH Error
Average Error for 10 RH
Average Error for 30 RH
Average Error for 60 RH
Average Error for 90 RH

[A8] Ultralife U9VL-J Three Test Runs



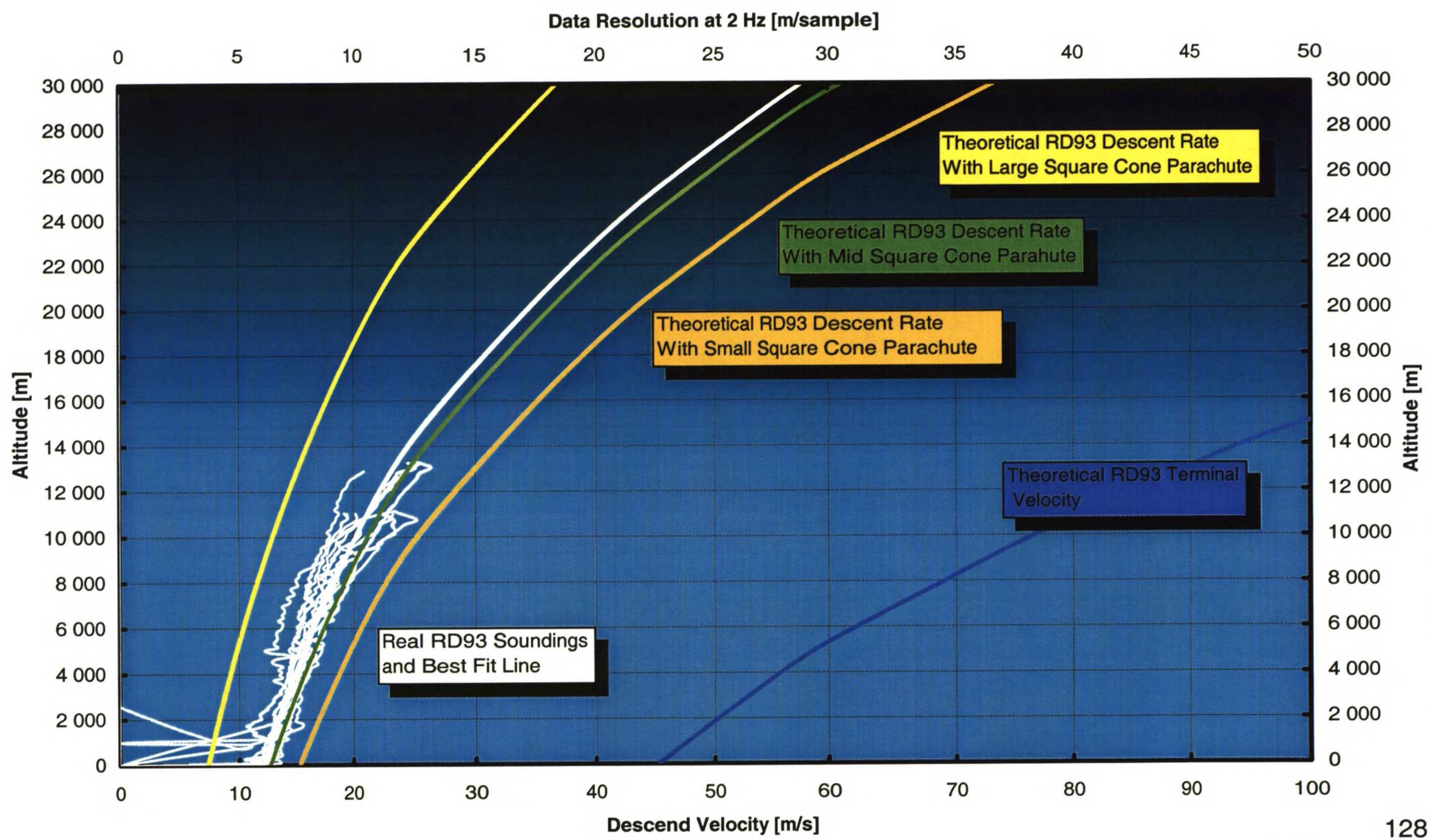
[A9] SAFT LSH14 Four Test Runs



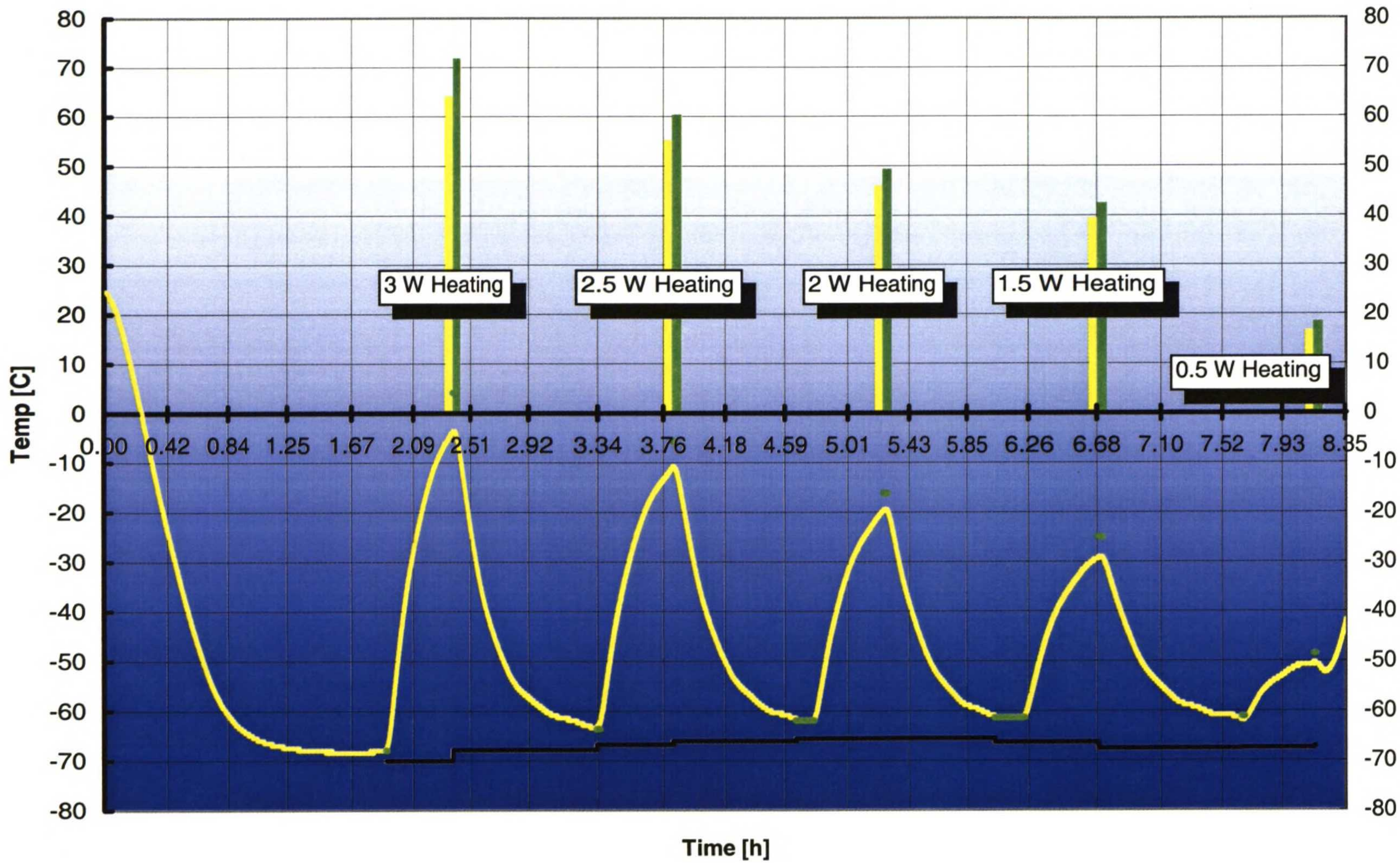


[A10] Duracell DL123 Three Test Runs
Original Output Voltage ~ 6 V
-72 C
-60 C
-50 C
Each step represents a +10 C increase in temperature
Output Voltage [V]
9
8
7
6
5
4
3
2
1
0
0.00
0.71
1.42
2.13
2.83
3.54
4.25
4.96
5.67
6.38
7.08
7.79
8.50
Time

[A11] RD93 Descend Rates



[A12] Dropsonde Inside Temperatures with Heaters



Ambient temperature was set to -72 C with 38 hPa pressure.

Temperature varied through the test session as indicated by the graph.

Heating time: 30 min
Cooling time: 1 h